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COOLING, HEATING, AND POWER SYSTEMS ENERGY PERFORMANCE AND NON-CONVENTIONAL EVALUATION BASED ON ENERGY USE

By

Nelson Fumo

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COOLING, HEATING, AND POWER SYSTEMS ENERGY PERFORMANCE AND NON-CONVENTIONAL EVALUATION BASED ON ENERGY USE

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Cooling, Heating and Power (CHP) systems have been recognized as a key alternative for thermal energy and electricity generation at or near end-user sites. CHP systems can provide electricity while recovering waste heat to be used for space and water heating, and for space cooling. Although CHP technology seems to be economically feasible, because of the constant fluctuations in energy prices, CHP systems cannot always guarantee economic savings. However, a well-designed CHP system can guarantee energy savings, which makes necessary the quantification of non-conventional benefits from this technology in order to offset any economic weakness that can arise as consequence of energy prices. Some aspects that could be included in a non-conventional evaluation are: building energy rating, emission of pollutants, power reliability, power quality, fuel flexibility, brand and marketing benefits, protection from electric rate hikes, and benefits from promoting energy management practices. This study focuses on two aspects: building energy rating and emission reduction of pollutants, related to CHP system energy performance. Two methodologies have been developed in order to estimate the energy related benefits from CHP technology. To determine the energy performance, a model has been developed and implemented to simulate CHP systems in order to estimate the building-CHP system energy consumption. The developed model includes the relevant variables governing CHP systems such as: type and size of the components, individual component efficiencies, system operating mode, operational strategy, and building demand for power, heating, and cooling. The novelty of this model is the introduction of the Building Primary Energy Ratio (BPER) as a parameter to implement a primary energy operational strategy, which allows obtaining the best energy performance from the building-CHP system. Results show that the BPER operational strategy always guarantees energy savings. On the other hand, results from a cost-oriented operational strategy reveal that for critical design conditions, high economic savings can be obtained with unacceptable increment of energy consumption. For Energy Star Rating and Leadership in Energy and Environmental Design (LEED) Rating, results show that CHP systems have the ability to improve both ratings.

Key words: CHP, energy performance, energy savings, energy ratings, BPER.

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NOMENCLATURE

BPER	Building primary energy ratio
CH	Absorption chiller
CHP	Cooling, heating, and power
CCHP	Combined cooling, heating, and power
COP	Coefficient of performance
CCS	Cooling coil system
cutoff	Fraction of PGU nominal power bellow which the unit not operate
DD	Degree-days
E	Electricity
EG	Electric grid
ECF	Site-to-primary energy conversion factor for electricity
ECR	Energy cost ratio
EIA	Energy Information Administration
F	Fuel
FCF	Site-to-primary energy conversion factor for fuel (natural gas)
HCS	Heating coil system
HVAC	Heating, ventilating, and air conditioning
I	Increment on size (PGU and CH)
MEC	Monthly energy consumption
P	Power (nominal power of the PGU)
PEC	Primary energy consumption
PES	Primary energy savings
PER	Primary energy ratio
PGU	Power generation unit
Q	Thermal energy (cooling or heating)

SEC	Site energy consumption
VC	Vapor compression system

Symbols

η	Efficiency level (ratio between useful output and input amount)
f	Fraction

Subscripts

b	Boiler
c	Cooling
ch	Chiller
chp	Cooling, heating, and power
f	Furnace
h	Heating (space and water); heating system (furnace, boiler)
hs	Space heating
hw	Water heating
np	Nominal power (of the PGU)
m	Meter
rec	Heat recovery system
p	Parasitic electricity
pgu	Power generation unit
R	Recovered (thermal energy)
Ra	Recovered and available (thermal energy for heating)
s	Space (heating or cooling)
vc	Vapor compression
yr	Year

CHAPTER I

INTRODUCTION

Dependence on imported energy, reliability and efficiency of energy systems, environmental concerns, and energy costs for end users, are factors that continually press for the improvement and development of new technologies, and new energy and environmental legislations (policies and regulations).

Cooling, Heating and Power (CHP) systems have been recognized as a key alternative for thermal energy and electricity generation at or near end-user sites. CHP systems are a form of distributed generation that can provide electricity while recovering waste heat to be used for space and water heating, and for space cooling by means of an absorption chiller. Since CHP systems generate the electricity on-site, losses due to transmission and distribution are considerably reduced compared with the electricity supplied by distant central power plants. While central power plants have a total efficiency between 30% - 51%, CHP systems are potentially 70% - 85% efficient in utilizing fuels [1].

General accepted benefits from the use of CHP systems are: increased energy efficiency, improved air quality, lower energy cost, increased power quality, and increased power reliability. Beyond these benefits, a non-conventional evaluation of CHP systems will show additional benefits such as building energy performance, fuel source flexibility, brand and marketing benefits, protection from electric rate hikes, and benefits from promoting energy management practices.

This study focuses on the benefits of using CHP systems that are directly related to the energy consumption, and more specifically to the energy consumption from the arrangement building and CHP system (building-CHP system). Although the results from this study can be applied for different type of buildings, this study concentrates on the use of CHP systems for office buildings. To evaluate any benefit from CHP systems related to energy consumption, the first step is to estimate the energy consumption. Chapter II presents the model and methodology to estimate the building energy consumption when a CHP system is installed. Chapter III presents the energy consumption and performance of the building-CHP system, while Chapter IV presents the analysis for cases when only the monthly energy consumption is known. Once the energy consumption has been defined, the methodologies presented in Chapter V are used to evaluate CHP systems based on building energy rating and emission of pollutants as part of a non-conventional evaluation. Finally, Chapter VI presents an uncertainty analysis of the CHP model developed in this investigation.

1.1 OBJECTIVES

- Develop a model to estimate the energy consumption profile when a CHP system is incorporated to the building and becomes part of the HVAC system.
- Develop a methodology to evaluate CHP systems energy performance based on primary energy consumption.

- Develop a methodology to evaluate CHP systems based on building energy ratings.
- Develop a methodology to estimate the emissions reduction of pollutants from the use of CHP systems.

1.2 BASIC DEFINITIONS

In this section important definitions such as: the site energy and primary energy are discussed. For CHP systems feasibility, economic analysis prevails without considering or quantifying other aspects and benefits from this technology. Economic analysis is based on the cost of the site energy; however promoters of CHP fail to show this technology saves *primary energy* rather than *site energy*.

1.2.1 Site Energy

The Energy Information Administration (EIA) [2] defines Site Energy as “The Btu value of energy at the point it enters the home, sometimes referred to as "delivered" energy. The site value of energy is used for all fuels, including electricity.”, and Site Energy Consumption (SEC) is defined as “The Btu value of energy at the point it enters the home, building, or establishment, sometimes referred to as "delivered" energy.” Building energy use is mainly a consequence of the building characteristics, use, operation, and climate conditions. The combination of these factors will give a unique amount and type of energy consumption for each building. SEC is referred to the energy consumed at the building doors, that is, the energy use registered by the utility meters.

CHP system design requires knowing the building energy consumption profiles or patterns for accurately sizing the components and modeling the system [1, 3 – 6]. Hourly energy consumption profiles are commonly used as a good reference for energy evaluation. For new buildings, or when the energy use is unknown, simulation software such as EnergyPlus^{TM} [7] can be employed to estimate the building energy consumption. For this study only electricity and natural gas are considered as site energy sources, although other energy sources such as fuels (propane, biofuels, fuel oil, etc.) or secondary energy (steam, hot water, etc.) can also be utilized. When a CHP system is incorporated to the building, it changes the site energy consumption profiles mainly because: (a) the electric energy consumed by the cooling system is substituted by fuel consumption; (b) the electric energy from the grid is substituted by electric energy from the power generation unit; and (c) the fuel consumption for heating is substituted by heat recovered from the power generation unit. For economic evaluations the site energy plays an important role because the energy consumption is billed based on the SEC.

1.2.2 Primary Energy

The EIA [2] defines Primary Energy as "All energy consumed by end users, excluding electricity but including the energy consumed at electric utilities to generate electricity. (In estimating energy expenditures, there are no fuel-associated expenditures for hydroelectric power, geothermal energy, solar energy, or wind energy, and the quantifiable expenditures for process fuel and intermediate products are excluded.)", and Primary Energy Consumption (PEC) is defined as "is the amount of site consumption, plus losses that occur in the generation, transmission, and distribution of energy." Primary energy reduction is important because it is related to the energy resources and environmental impact. In fact, Energy Star [8], a government-backed program uses primary or source energy as the basis for benchmarking buildings energy performance. In concordance with Energy Star, the standard site-to-primary energy or site-to-source energy conversion factors are applied as national averages and it is stated that the application of these national averages is consistent with the objective of comparing the total annual energy consumption among buildings with similar operations. In this study, the site-to-primary energy conversion factors, presented in Table 1.1, correspond to those obtained from Target Finder [9] for office type commercial buildings.

Table 1.1 Site-to-Primary Energy Conversion Factors

Fuel Type	Conversion Factor [a]
Electricity	3.343
Natural Gas	1.047
Propane	1.010
Fuel Oil (No. 2)	1.010
Diesel (No. 2)	1.010
Wood	1.000

a. Values obtained in January 2008

In the evaluation of any energy system, primary energy has more significance than site energy because it is related to the energy resources and the environment. For example, electricity as site source does not show that more than three times of the energy is being used at the origin; and while electricity as site source has zero emissions at the origin, it has significant amount of pollutants released into the environment.

1.3 CASE STUDY

For CHP system analysis, a reference building was defined in order to compare the energy consumption for the cases without and with the implementation of a CHP system. Section 1.3.1 describes how the energy consumption was obtained for the reference building considered in this study.

The energy consumption profile of a building is highly dependent on the climate conditions. Therefore, to consider the energy consumption patterns in the analysis of CHP systems, Section 1.3.2 describes the methodology used to account for climate conditions.

In this study, CHP systems are considered as distributed generation systems with the advantage that waste thermal energy from the prime mover is recovered for space cooling and heating. Therefore, to account for the effect of the power generation unit (PGU) on the CHP system energy performance, three efficiency values were considered: 0.25, 0.30, and 0.35. These values were chosen as representative of general efficiencies for common commercially available PGU.

1.3.1 Actual Building Energy Consumption

To obtain hourly site energy consumption data a hypothetical building was simulated using the software EnergyPlus [7]. General description of the building is presented in Table 1.2. Excel files containing the hourly energy consumption from the EnergyPlus simulations were used in the CHP system simulation model presented in Section 2.4.

Table 1.2 General Description of the Simulated Building Using EnergyPlus

Orientation	Aligned with North
Building type	General Offices
Area	1156 m^2 (34 m x 34 m)
Glass area	30% in each wall (windows and door)
People	115 for weekdays, 0 for weekend
Occupancy schedule	Until (fraction): 6 (0), 7 (0.1), 8 (0.5), 12 (1), 13(0.5), 16(1), 17 (0.5), 18 (0.1), 24 (0)
Electric equipment	15000 W
Equipment schedule	Same as for occupancy
Lights	45,000 W
Lights schedule	Until[a] (fraction)[b]: 6 (0.05), 7 (0.2), 17 (1), 18 (0.5), 24 (0.05); for weekends 24 (0.05)
Thermostat schedule:	
For heating	Until[a] (set point, °C)[c]: 6 (18), 22 (22), 24 (18)
For cooling	Until[a] (set point, °C)[c]: 6 (28), 22 (24), 24 (28)

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

1.3.2 Climate Conditions

Climate is one of the variables that define the energy consumption profiles (electric and thermal energy demand) of a building. To analyze the effect of the energy consumption profiles on CHP systems energy performance, the same building was simulated using weather data for the cities presented in Table 1.3, and pointed in the map of climate zones of the U.S.A. shown in Figure 1.1. Table 1.3 also presents the zip code chosen to identify each city. This parameter is required in some calculation along this study.

Table 1.3 Cities and Respective Zip Codes Identifying Climate Zones

Climate Zone	City	Zip Code
1	Denver, CO	80210
2	Chicago, IL	60610
3	Sterling, VA	20165
4	San Francisco, CA	94110
5	Tampa, FL	33610

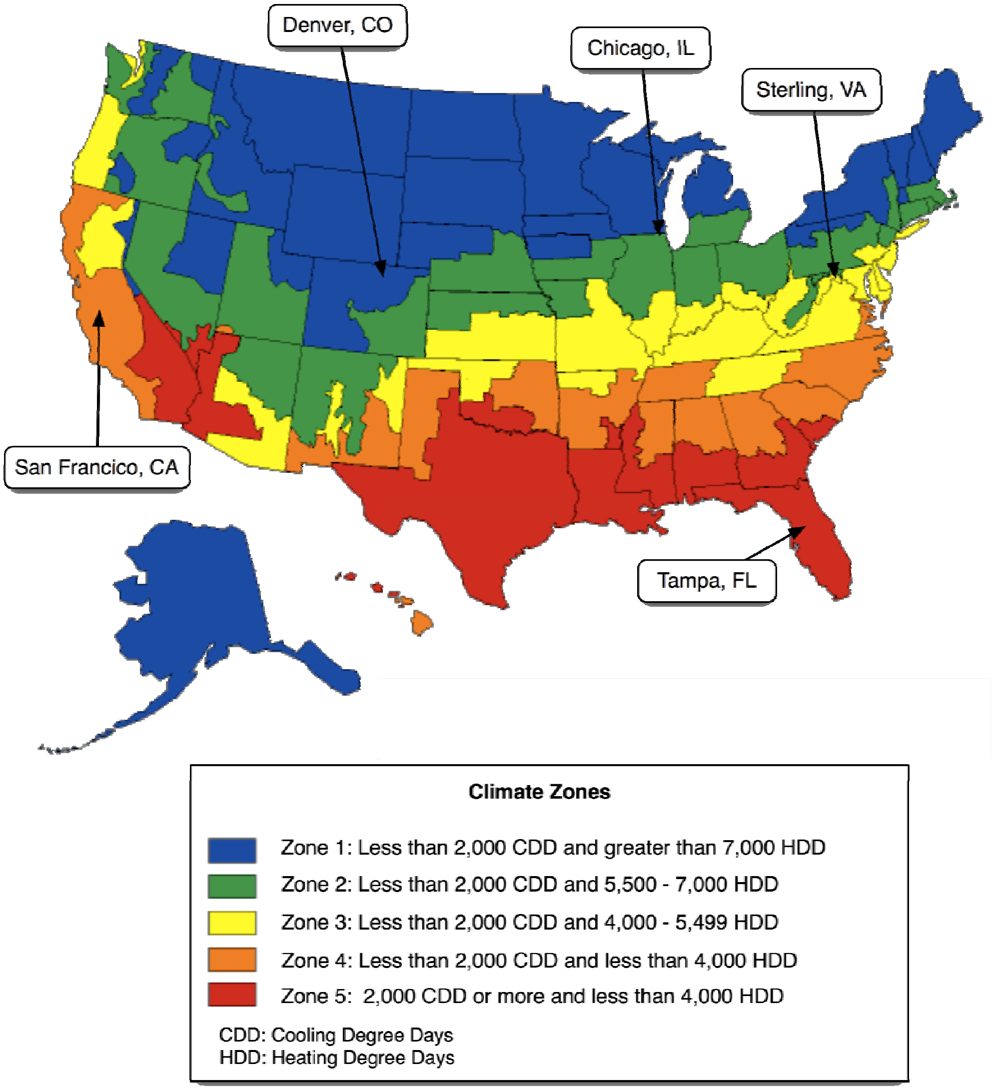


Figure 1.1 Cities Representing the Climate Zones of the U.S.A.
Adapted from U. S. Climate Zones for 2003 CBECS, Energy Information Administration, DOE
http://www.eia.doe.gov/emeu/cbecs/climate_zones.html (April 10, 2008)

CHAPTER II

BUILDING-CHP SYSTEM SIMULATION

2.1 INTRODUCTION

The design and analysis of CHP systems is simplified by using models, which can be used to develop computer software for simulation purpose, allowing the reduction of time analysis. CHP system analysis involves variables such as type and size of the components, individual component efficiencies, system operating mode, operational strategy, and building demand for power, heating, and cooling loads [10 – 15]. These seem to be the most relevant variables to consider when designing and estimating the performance of CHP systems.

For a CHP system, common operation modes are electric load following, electrically sized, or thermally sized [16]. For the electric load following operation mode the power generation unit (PGU) is able to handle the variations on the electric demand. The electrically sized operation mode is a "base loaded" operation. The thermally sized operation mode is a "following thermal demand" operation. For this study, the model is based on the electric load following operation mode. This operation mode was chosen for two reasons. First, in order to optimize the energy performance of the CHP system, the model was implemented to account for different PGU and the absorption chiller (CH) sizes. Second, because other operation modes frequently results in more production of power than needed by the building, which require either selling electricity back to the grid or electric power storage, they are beyond the scope of this study. Thus, the electric load following operation mode was applied in the simulations performed.

CHP operational strategy defines the goal of the system's response to the energy demand, which is one of the factors that characterize the energy performance of the system. The most frequent operational strategy is cost-oriented, although a primary energy operational strategy yields a better energy performance. Cardona and Piacentino [17] presented a summary of the most common evaluation criteria for combined heat and power plants and combined cooling, heating, and power plants (CCHP). They reported that the primary energy saving management strategy is the operational strategy that allows achieving maximum energy savings during the plant life cycle. Other studies [18 – 20] also consider primary energy as the appropriate criterion for evaluation of CHP systems. Sun et al. [18] compared the thermal efficiency of separated cooling and heating system versus the combined system. They stated that "to compare systems with different types of driving and produced energy, the primary energy rate (PER) is a satisfactory criterion." The PER is defined as the ratio of the required output to the primary energy demand. For estimating the PER for electrical equipment they considered the efficiency of generation and distribution of electricity, which can be compared to the inverse of site-to-primary energy conversion factor used in this study. Sun et al. [18] and Li et al. [20] compared the energy utilization evaluation of separated systems versus combined cooling, heating and power, but using the fuel energy ratio which considers total primary energy use. As suggested by Li et al. [20], when comparing energy performance, primary energy savings "… is not mainly resulted from the performance of CCHP systems but the difference of primary energy."

Accordingly, in this study CHP system energy performance is evaluated based on primary energy consumption and a primary energy strategy is implemented to optimize energy consumption. Therefore, a model is developed for the analysis of CHP systems. The model accounts for the variables that govern the exchange and use of energy for the CHP system components and other components of the building HVAC system. A new parameter called Building Primary Energy Ratio (BPER) is introduced to evaluate the CHP system energy performance under a primary energy operational strategy.

2.2 MODEL FOR AN HOUR TIME STEP ENERGY CONSUMPTION ANALYSIS

The building-CHP system site energy consumption is computed based on the energy consumption measured at the utility meters. The model uses the actual building energy consumption to estimate the energy consumption for the case when a CHP system is incorporated. The model is derived based on the building-HVAC system and the building-CHP system sketched in Figures 2.1 and 2.2, respectively.

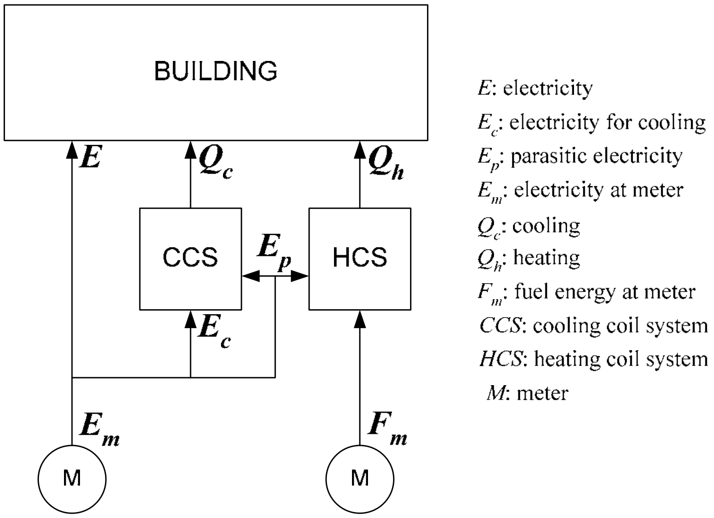


Figure 2.1 Building-HVAC System Arrangement

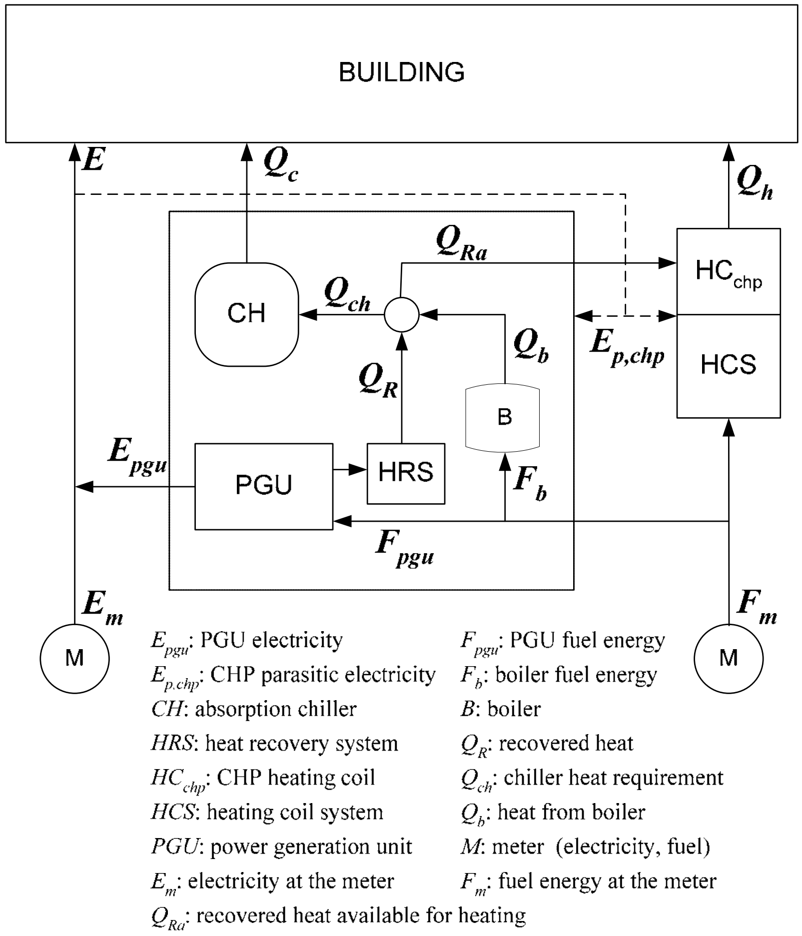


Figure 2.2 Building-CHP System Arrangement

The efficiency of the PGU, η_{pgu}, is considered as the fuel to electricity conversion efficiency, and the efficiency of the boiler, η_b, is considered as the thermal efficiency. The efficiency of the heat recovery system, η_{rec}, and the HVAC heating system (furnace or boiler), η_h, are considered as the relation between the thermal energy gain by the working fluid and the available thermal energy for heat transfer from the source. All fuel use is considered as a thermal energy source at the fuel lower heating value.

The grid electric energy use at the meter, E_m , can be determined as

$$E_m = E + E_{p,chp} - E_{pgu} \tag{2.1}$$

where E is the building electric energy consumption (electric equipment, lights, etc), E_{pgu} is the electric energy generated by the PGU, and $E_{p,chp}$ is the CHP parasitic electricity. For the hour time step simulation, the electric energy demand from the PGU is assumed to be equal to the energy consumption for the specific hour. The actual HVAC system parasitic electric energy, E_p, is increased by a factor $F_{p,c}$ when cooling is required, and by a factor $F_{p,h}$ when heating is required. Then, for cooling demand the CHP system parasitic electricity is estimated as

$$E_{p,chp} = E_p \cdot F_{p,c} \tag{2.2}$$

and for heating demand the CHP parasitic electricity is estimated as

$$E_{p,chp} = E_p \cdot F_{p,h} \tag{2.3}$$

When a CHP system is incorporated, most of the original parasitic electricity demand remains as part of the HVAC air distribution system. For the heating mode of CHP systems, additional electric energy is required by the new equipment to recover the waste heat from the prime mover. For the cooling mode of CHP systems, more electric energy is required compared with the heating condition because of the additional equipment associated with the absorption chiller. Therefore, in general, $F_{p,c}$ is greater than $F_{p,h}$.

The electric energy produced by the PGU is estimated using Equation (2.4):

$$E_{pgu} = 0 \quad \text{if} \quad E + E_{p,chp} < cutoff \cdot E_{np,pgu} \tag{2.4a}$$

$$E_{pgu} = E + E_{p,chp} \quad \text{if} \quad E + E_{p,chp} < E_{np,pgu} \tag{2.4b}$$

$$E_{pgu} = E_{np,pgu} \quad \text{if} \quad E + E_{p,chp} > E_{np,pgu} \tag{2.4c}$$

where $cutoff$ refers to the fraction of the nominal power below which the PGU should not operate; and $E_{np,pgu}$ is the energy produced by the PGU during an hour at the nominal energy rate (nominal power, P_{pgu}). Numerically $E_{np,pgu}$ corresponds to $E_{np,pgu} = P_{pgu} \cdot 1hr$.

The PGU fuel energy consumption is estimated as

$$F_{pgu} = \frac{E_{pgu}}{\eta_{pgu}} \tag{2.5}$$

where η_{pgu} is the PGU thermal efficiency. The efficiency of the power generation unit is assumed to be constant independently of the electric demand. Then, the ratio between electricity and fuel remains constant for any demand higher than the $cutoff$ fraction of the nominal power of the PGU.

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

$$Q_{ch} = \frac{COP_{vc}}{COP_{ch}} E_c \tag{2.6}$$

where COP_{ch} and COP_{vc} represent the coefficient of performance of the absorption chiller and vapor compression system, respectively; and E_c is the electric energy consumption for cooling from the vapor compression system. Equation (2.6) defines the amount of heat required by the absorption chiller to provide the same cooling as the vapor compression system for any specific time of analysis.

The recovered waste heat from the prime mover is estimated as

$$Q_R = F_{pgu} \cdot \eta_{rec} \left(1 - \eta_{pgu}\right) \tag{2.7}$$

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

The recovered thermal energy corresponds only to the useful energy, that is, the heat required by the absorption chiller, and heat required for space heating. For the cases when the recovered thermal energy is greater than the total heat required, Q_R is set equal to the total heat required.

The priority for the use of the recovered thermal energy is the heat required by the absorption chiller. Then, the thermal energy recovered and available for space heating, Q_{Ra}, will exist only when the recovered thermal energy is greater than the chiller heat consumption

$$Q_{Ra}^{+} = Q_R - Q_{ch} \tag{2.8}$$

The fuel energy saving from the waste thermal energy recovered is estimated using the efficiency of the heating system, η_h, and is determined as

$$F_{Ra} = \frac{Q_{Ra}}{\eta_h} \tag{2.9}$$

When the recovered thermal energy does not satisfy the requirement of the absorption chiller, additional heat is provided by the boiler of the CHP system. The boiler fuel energy consumption is computed as

$$F_b = \frac{Q_{ch} - Q_R}{\eta_b} \tag{2.10}$$

where η_b is the boiler thermal efficiency.

The fuel energy consumption required to provide the heat needed by the building is

$$F_h = \frac{Q_h}{\eta_h} \tag{2.11}$$

Then, the fuel energy consumption registered at the meter is estimated as

$$F_m = F_h + F_{pgu} + F_b - F_{Ra} \tag{2.12}$$

2.2.1 Evaluation of Primary Energy

Thermal energy efficiency from the use of CHP systems has to be assessed through primary energy consumption. Therefore, the building primary energy consumption (*PEC*) is determined, for the actual building energy consumption (subscript 1) and building-CHP system energy consumption (subscript 2), as

$$PEC_1 = E_{m1} \cdot ECF + F_{m1} \cdot FCF \tag{2.13}$$

$$PEC_2 = E_{m2} \cdot ECF + F_{m2} \cdot FCF \tag{2.14}$$

where *ECF* and *FCF* are the site-to-primary energy conversion factors for electricity and natural gas, respectively. In this study, the site-to-primary energy conversion factor correspond to those used by the Energy Star program (Table 1.1); however, more specific conversion factors for electricity could be used based on the fuel mix of the power plant feeding the grid.

2.2.2 Primary Energy Strategy

In this study, the definition of Building Primary Energy Ratio (*BPER*) is introduced as a new parameter to evaluate CHP systems energy performance under a primary energy operational strategy. *BPER* is defined as

$$BPER = \frac{PEC_1}{PEC_2} \tag{2.15}$$

For values of *BPER* higher than 1, the use of a CHP system reduces the primary energy consumption, and for *BPER* values lower than 1, the use of a CHP system causes an increase of the primary energy consumption.

2.3 MODEL FOR A MONTHLY ENERGY CONSUMPTION ANALYSIS

When hourly energy consumption is not available, monthly energy consumption can be utilized to estimate CHP system energy consumption. Results for a monthly basis must be used as a guide to decide if further effort is convenient. The hourly model can be adjusted to monthly energy consumption, but because of the lack of information between the match of electricity and thermal demand, only those equations that do not require specific hourly data are useful. For all equations in this section, the variables related to energy consumption must be computed as monthly values.

The grid electric energy use at the meter, E_m , can be determined as

$$E_m = E - E_{pgu} \tag{2.16}$$

The PGU fuel energy consumption is estimated using Equation (2.5).

The heat required by the absorption chiller to handle the cooling load is estimated as in Equation (2.6), $Q_{ch} = \frac{COP_{vc}}{COP_{ch}} E_c$, where E_c is the monthly electric energy consumption for cooling.

The recovered waste heat from the prime mover is estimated using Equation (2.7).

The heat recovered and available for space heating is estimated using Equation (2.8).

The fuel energy saving from the thermal energy recovered is determined using Equation (2.9).

The boiler fuel energy consumption is computed using Equation (2.10).

The fuel energy consumption registered at the meter is estimated using Equation (2.12), with F_h as in Equation (2.11).

2.3.1 Methodology to Estimate the Monthly Heating and Cooling Energy Consumption from Annual Data

Sources of information about buildings energy consumption, such as the Building Energy Data Book [21] and ASHRAE 2003 [22], normally present the data on a yearly basis. Analysis of CHP system based on annual energy use most probably will lead to a wrong analysis because most of the cooling load and heating load for space conditioning will occur in different months. Therefore, some methodology should be applied to estimate the monthly energy consumptions. Once the monthly energy consumptions have been estimated, the model described previously can be applied. To estimate the building electric energy consumption, the annual electricity can be distributed proportionally among the months. To estimate the monthly energy consumption for heating and cooling, the Monthly Degree-Days method presented in ASHRAE 2005 [23] is proposed and developed in this section. To apply this method, the monthly ambient average temperatures have to be known. The degree-days method is related to the space heating and space cooling and does not allow having both for the same month. To account for any water heating use when space heating is not required, this methodology uses the heating degree-days to estimate the fuel energy consumption for water heating even when space cooling degree-days exists.

The Monthly Degree-Days method can be applied as follows:

Monthly Heating Degree-Days

$$DD_h(t_{bal}) = \sigma_m N^{1.5}\left[\frac{\phi_h}{2} + \frac{\ln\left(e^{-a\phi_h} + e^{a\phi_h}\right)}{2a}\right] \tag{2.17}$$

Monthly Cooling Degree-Days

$$DD_c(t_{bal}) = \sigma_m N^{1.5}\left[\frac{\phi_c}{2} + \frac{\ln\left(e^{-a\phi_c} + e^{a\phi_c}\right)}{2a}\right] \tag{2.18}$$

where $a = 1.698\sqrt{day/month}$, σ_m is the standard deviation for each month, N is the number of days in the month, ϕ is a normalized temperature, and $\bar{t}_{bal}$ is the balance point temperature. The balance point temperature is defined as "the value of the outdoor temperature $\bar{t}_o$ at which, for the specified value of the interior temperature t_i, the total heat loss q_{gain} is equal to the heat gain from sun, occupants, lights, and so forth." [23]

The monthly heating degree-days for space heating are determined as

$$\begin{cases} if\ \bar{t}_o > t_{bal} & \left(DD_h\right)_s = 0 \\ if\ \bar{t}_o < t_{bal} & \left(DD_h\right)_s = DD_h \text{ (Equation 2.17)} \end{cases} \tag{2.19}$$

where $\bar{t}_o$ is the monthly average ambient temperature.

The monthly heating degree-days for water heating are determined as

$$(DD_h)_w = DD_h \tag{2.20}$$

The monthly cooling degree-days for space cooling are determined as

$$\begin{cases} if\ \bar{t}_o < t_{bal} & \left(DD_c\right)_s = 0 \\ if\ \bar{t}_o > t_{bal} & \left(DD_c\right)_s = DD_c \text{ (Equation 2.18)} \end{cases} \tag{2.21}$$

The standard deviation for each month can be calculated as

$$\sigma_m = 3.54 - 0.029\bar{t}_o + 0.0664\sigma_{yr} \tag{2.22}$$

where σ_{yr} is the standard deviation of the monthly average temperature about the annual average, defined as

$$\sigma_{yr} = \sqrt{\frac{1}{12}\sum_{1}^{12}\left(\bar{t}_o - \bar{t}_{o,yr}\right)^2} \tag{2.23}$$

where $\bar{t}_{o,yr}$ is the annual average temperature.

The normalized temperature for heating and cooling are

For heating
$$\phi_h = \frac{\bar{t}_{bal} - \bar{t}_o}{\sigma_m\sqrt{N}} \tag{2.24}$$

For cooling
$$\phi_c = \frac{\bar{t}_o - \bar{t}_{bal}}{\sigma_m\sqrt{N}} \tag{2.25}$$

The monthly energy use for space heating is estimated as

$$Q_{hs} = \frac{Q_{hs,yr}(DD_h)_s}{\sum_{1}^{12}(DD_h)_s} \tag{2.26}$$

where $Q_{hs,yr}$ is the building annual energy use for space heating.

The monthly energy use for water heating is estimated as

$$Q_{hw} = \frac{Q_{hw,yr}(DD_h)_w}{\sum_{1}^{12}(DD_h)_w} \tag{2.27}$$

where $Q_{hw,yr}$ is the building annual energy use for water heating.

The building monthly energy use for heating is expressed as

$$Q_h = Q_{hs} + Q_{hw} \tag{2.28}$$

The fuel consumption required to provide the heat needed by the building, F_h, is found using Equation (2.11), $F_h = \frac{Q_h}{\eta_f}$.

The monthly energy use for space cooling is estimated as

$$Q_c = \frac{Q_{c,yr}(DD_c)_s}{\sum_1^{12}(DD_c)_s} \tag{2.29}$$

where $Q_{c,yr}$ is the building annual energy use for space cooling.

The electric energy consumption for cooling, E_c, can be found using the coefficient of performance for the vapor compression system, COP_{vc}, as

$$E_c = \frac{Q_c}{COP_{vc}} \tag{2.30}$$

Once the actual building monthly energy use, electricity and natural gas consumption, have been estimated from the building annual energy consumption, as mentioned, the model for a monthly energy use analysis can be applied.

2.4 SIMULATION PROGRAM

Based on the developed model for an hour time step energy use analysis, a simulation program was developed according with the logic of the flowchart presented in Appendix A. The sub-index “1” represents the actual building energy consumptions, that is, without CHP system. The sub-index “2” represents the case for the building-CHP system operating without the BPER operational strategy. The sub-index “3” represents the case for the building-CHP system operating with the BPER operational strategy.

The inputs for the simulation program are:

- Heat recovery system efficiency, η_{rec}
- Vapor compression coefficient of performance, COP_{vc}
- Absorption chiller coefficient of performance, CPO_{ch}
- CHP boiler efficiency, η_b
- Heating system efficiency, η_h
- Increasing factors for parasitic electricity, $F_{p.c}$ and $F_{p.h}$
- PGU cutoff fraction, $cutoff$
- PGU efficiency, η_{pgu}
- Site-to-primary energy conversion factors, ECF and FCF
- Excel file with the following energy consumption information:
    - Building electric energy consumption, E.
    - HVAC parasitic electricity, E_p.
    - Vapor compression electricity for cooling, E_c.
    - Fuel energy consumption for heating, F_h.
    - Building fuel energy consumption for not heating use, F.

With the exception of the building energy consumption, the input values used in this study are presented in Table 2.1.

Table 2.1 Input Values for CHP System Simulation Program

Variable	Symbol	Value
Heat recovery system efficiency	η_{rec}	0.8
Vapor compression coefficient of performance	COP_{vc}	3
Absorption chiller coefficient of performance	CPO_{ch}	0.7
CHP boiler efficiency	η_b	0.8
Heating coil system efficiency	η_h	0.8
Cooling factor for parasitic electricity	$F_{p.c}$	1.4
Heating factor for parasitic electricity	$F_{p.h}$	1.2
PGU cutoff fraction	$cutoff$	0.25
PGU efficiency	η_{pgu}	0.25, 0.30, 0.35
Electricity energy conversion factor	ECF	3.343
Fuel energy conversion factor	FCF	1.047

The simulation program allows the analysis for different PGU and CH sizes in order to define the condition for best energy performance. Therefore, some equations of the model must be adjusted to account for this condition. The PGU and CH sizes are varied from zero to the maximum required capacity. PGU and CH sizes of zero represent the case when the CHP system does not exist. The maximum PGU size is calculated based on the maximum building electric energy consumption because no electricity is sold to the grid. While the maximum CH size is calculated based on the maximum vapor compression electric energy consumption for cooling. The size increments for the PGU (I_{pgu}) and CH (I_{ch}) can be defined by the user as an entry, but by default are 5 and 2, respectively. For each CH size the proportion of the cooling load to be handled by the absorption chiller and vapor compression system are defined. The model gives priority to the absorption chiller to handle the cooling load. If the chiller is providing the maximum cooling, but the cooling load is not satisfied, the difference is handled by the vapor compression system.

To incorporate the building primary energy operational strategy two steps must be followed. The first step is to compute the building primary energy ratio parameter (BPER, see Section 2.2.2) using the primary energy consumption for the building without CHP system (PEC_1), and the primary energy consumption for the building-CHP system (PEC_2). Based on the sub-indices assigned to identify the energy consumption condition, the computed BPER is identified as $BPER_{12}$. If the $BPER_{12}$ is higher or equal to 1, the grid electric energy use at the meter, and the fuel energy consumption registered at the meter, remain as calculated for the building-CHP system assuming that the CHP system was operating as prescribed. However, if the $BPER_{12}$ is lower than 1, the actual electric energy consumption (E_{m1}) is set as the building-CHP system energy consumption assuming that the PGU was not operating. When the PGU does not operate, no heat is recovered from the prime mover. Therefore, when cooling demand exists, the boiler of the CHP system must supply the heat required by the absorption chiller. For this condition, the fuel energy consumption is the actual fuel energy consumption plus the boiler fuel energy consumption ($F_{m1}+F_b$). However, because of the low energy conversion efficiency from fuel energy to cooling through the absorption chiller, more primary energy could be consumed if the PGU is not operating. Therefore, the next step is to define if the PGU must operate even though the $BPER_{12}$ is lower than 1. To accomplish this, the BPER is now calculated using the PEC_2 and the primary energy consumption for the case when the PGU of the CHP system is not operating (PEC_3). Then, based on the sub-indices assigned to identify the new energy consumption condition, the new BPER is identified as $BPER_{23}$. If the $BPER_{23}$ is higher or equal to 1, the energy consumption is set as those values calculated if the PGU is not operating (E_{m3} and F_{m3}). If the $BPER_{23}$ is lower than 1, the energy consumption is set as those values calculated for the CHP system operating as prescribed (E_{m2} and F_{m2}).

A block diagram for general description of the structure for the simulation of the building-CHP system is presented in Figure 2.3.

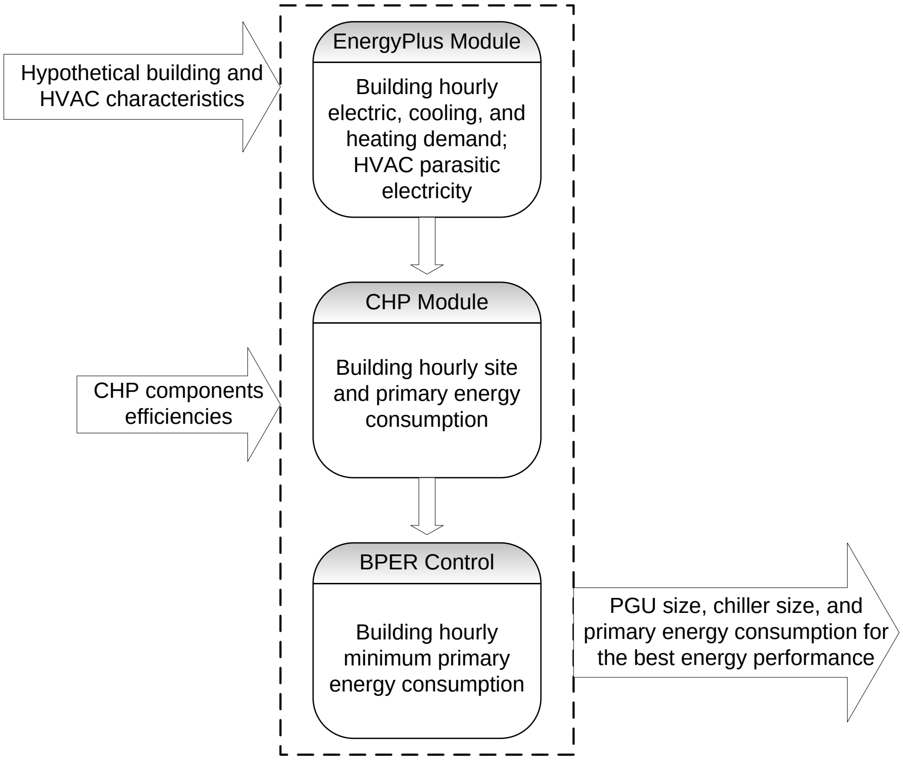


Figure 2.3 Block Diagram for the Building-CHP System Simulation

2.5 CONCLUSION

The model to estimate the energy consumption profile when a CHP system is incorporated to the building and becomes part of the HVAC system was developed. The model includes the methodology to evaluate CHP energy performance based on primary energy consumption.

Beyond the initial objectives of this research, the implementation of the building primary energy ratio (BPER) operational strategy is a contribution that allows optimizing CHP systems energy performance. Besides, the simulation program developed to implement the model has the advantage that simulates the systems for different power generation unit and absorption chiller sizes in order to obtain the best design configuration.

The concept of BPER can also be used for optimum economic design. By changing the energy conversion factors (ECF and FCF) by energy price, the concept of energy cost ratio (ECR) is derived. If this definition, instead of the BPER, is used in the simulation program, the results would correspond to the design with lower energy cost. This factor, ECR, was used to obtain the results that allowed the comparison of the energy performance between the CHP system best energy performance and the CHP system best economic option.

CHAPTER III

CHP SYSTEM ENERGY PERFORMANCE

3.1 INTRODUCTION

CHP system analysis involves variables related to the components of the system, operation of the system, and building characteristics. The interrelation among all variables will define the system performance. Adequate designs must yield economical savings but, more importantly, they must yield real energy savings based on the best energy performance. In this chapter site energy consumption, primary energy consumption, and system efficiency are the variables considered to evaluate the CHP system energy performance. Since, generally, the economic analysis prevails in the feasibility of CHP systems, the energy cost is also considered to show that economic decisions could yield misleading results.

The results are presented and compared for the cases when the CHP runs without and with the building primary energy ratio (BPER) operational strategy. These two cases are identified as CHP and CHP-BPER, respectively. Based on the nomenclature of the simulation software, sub-index 2 and 3 corresponds to CHP and CHP-BPER, respectively. As mentioned in Chapter II, when the PGU and CH sizes are zero, the results correspond to the case when the CHP system does not exist and it is identified as sub-index 1.

The simulation software varies the power generation unit (PGU) and absorption chiller (CH) sizes to find the sizes that yield the best energy performance for each particular case of inputs. The additional electric energy and cooling energy required by the building for any particular hour of analysis are provided by the electric grid (EG) and vapor compression system (VC), respectively. Table 3.1 summarizes the PGU, CH, and VC sizes, and the maximum electric power demanded from the grid for the best energy performance. The optimized parameters in Table 3.1 are used to develop further results, which are discussed in this chapter.

Table 3.1 PGU, CH, and VC Sizes, and EG Demand for Best Energy Performance

		Size (kW)							
	PGU Efficiency	CHP				CHP-BPER			
City/Zone		PGU	EG	CH	VC	PGU	EG	CH	VC
Denver Zone 1	0.25	15	85	8	28	15	85	8	28
	0.30	50	50	22	14	50	50	22	14
	0.35	75	25	22	14	75	25	22	14
Chicago Zone 2	0.25	15	90	8	34	15	90	8	34
	0.30	50	55	22	20	50	55	22	20
	0.35	80	25	22	20	80	25	22	20
Sterling Zone 3	0.25	15	100	8	40	15	100	8	40
	0.30	50	65	22	26	50	65	22	26
	0.35	80	35	22	26	80	35	22	26
San Francisco Zone 4	0.25	10	75	6	20	10	75	6	20
	0.30	35	50	16	10	35	50	16	10
	0.35	65	20	20	6	65	20	20	6
Tampa Zone 5	0.25	15	100	8	42	15	100	8	42
	0.30	25	90	10	40	25	90	10	40
	0.35	75	40	22	28	75	40	22	28

Table 3.1 shows that for PGU and CH size increments of 5 and 2 respectively, the design for best energy performance is the same for the cases when the system run without (CHP) and with the BPER operational strategy (CHP-BPER). However, since different

PEC is obtained, the design will not necessarily be always the same for both cases. To understand Table 3.1, the case for Tampa with PGU efficiency of 0.25 is explained. Based on the inputs required by the developed simulation model, the design is specified with a CHP size of 15 kW and a CH size of 8 kW. The required electric power from the grid (EG) to match the maximum electric demand is 100 kW. Similarly, the vapor compression system (VC) capacity to match the maximum cooling demand is 42 kW.

3.2 SITE ENERGY CONSUMPTION

The most common criterion to implement any energy conservation system is economic. However, a CHP system economic evaluation could yield misleading results when the main goal is energy resources conservation and environmental protection. As mentioned in Section 1.2.1, CHP systems changes the building site energy consumption profiles by increasing the use of fuel, while reducing the use of electricity from the grid. However, CHP systems increase the total building site energy consumption. Therefore, because the economic evaluation is based on site energy price, generally the feasibility of CHP system relies on energy cost and not in actual energy saving.

3.2.1. CHP Systems Increase Site Energy Consumption (SEC)

As part of the CHP system energy performance analysis, this section demonstrates that CHP systems always increase the building site energy consumption.

From Figure 2.1 the building electric energy consumption at the meter is

$$E_{m1} = E + E_c + E_p \tag{3.1}$$

while the building-CHP electric energy consumption at the meter is

$$E_{m2} = E + E_{p,chp} - E_{pgu} \tag{3.2}$$

Combining Equations (3.1) and (3.2) yields

$$E_{m2} = (E_{m1} - E_c) + (E_{p,chp} - E_p) - E_{pgu} \tag{3.3}$$

The increment of the parasitic electric energy, $E_{p,chp} - E_p$, can be defined as a fraction of the electric energy generated by the PGU as

$$E_{p,chp} - E_p = f_p E_{pgu} \tag{3.4}$$

Then, Equation 3.3 can be written as

$$E_{m2} = (E_{m1} - E_c) - E_{pgu}(1 - f_p) \tag{3.5}$$

From Figure 2.2 the fuel consumption at the meter is computed as

$$F_{m2} = F_{m1} + F_{pgu} + F_b - \frac{Q_{Ra}}{\eta_h} \tag{3.6}$$

where F_{m1} corresponds to the building fuel energy consumption.

The total site energy consumption variation is found by combining Equations (3.5) and (3.6)

$$\left(E_{m2} + F_{m2}\right) - \left(E_{m1} + F_{m1}\right) = F_{pgu} - E_c + F_b - E_{pgu}\left(1 - f_p\right) - \frac{Q_{Ra}}{\eta_h} \tag{3.7}$$

Defining the total site energy consumption variation as ΔSEC, and using Equations (2.5) and (2.6), Equation (3.7) can be written as

$$\Delta SEC = F_{pgu} - \frac{COP_{ch}}{COP_{vc}} Q_{ch} + F_b - F_{pgu}\eta_{pgu}\left(1 - f_p\right) - \frac{Q_{Ra}}{\eta_h} \tag{3.8}$$

By rearranging Equation (3.8), the general equation for the building-CHP system operation that allows estimating the total site energy consumption variation is

$$\Delta SEC = F_{pgu}\left[1 - \eta_{pgu}\left(1 - f_p\right)\right] + F_b - \frac{COP_{ch}}{COP_{vc}} Q_{ch} - \frac{Q_{Ra}}{\eta_h} \tag{3.9}$$

Equation (3.9) is the general equation that can be used to estimate the SEC for the building-CHP system for any operating condition of the CHP system. Since CHP system is an electric power source with the advantage of providing thermal energy for heating and cooling, three operating conditions can be defined:

- Operating condition 1: cooling, heating, and power.
- Operating condition 2: heating and power.
- Operating condition 3: cooling and power.

To simplify the deduction that CHP systems increase the SEC, Equation (3.9) is analyzed individually for each operating condition.

Operating condition 1: Cooling, heating, and power.

This condition corresponds to the case when the building demands cooling and heating. When the recovered thermal energy from the CHP system is used for space conditioning, based on the hour by hour analysis, the building will never demand cooling and heating loads at the same time. Therefore, this operating condition most probably would occur when space cooling and hot water are required for office buildings.

By looking at Figure 2.2, and understanding the logic of the model described in Section 2.2, when the CHP system provides cooling and heating, $F_b = 0$ and $Q_{Ra} = Q_R - Q_{ch} \neq 0$. By substituting these two terms into Equation (3.9), and using Equation 2.7, for this operating condition the site energy consumption variation is defined as

$$\Delta SEC = F_{pgu}\left[1-\eta_{pgu}\left(1-f_p\right)\right]-\frac{COP_{ch}}{COP_{vc}}Q_{ch}-F_{pgu}\left(1-\eta_{pgu}\right)\frac{\eta_{rec}}{\eta_h}+\frac{Q_{ch}}{\eta_h} \qquad (3.10)$$

By rearranging Equation (3.10), it can be rewritten as

$$\Delta SEC = F_{pgu}\left[1-\eta_{pgu}\left(1-f_p\right)-\left(1-\eta_{pgu}\right)\frac{\eta_{rec}}{\eta_h}\right]+Q_{ch}\left(\frac{1}{\eta_h}-\frac{COP_{ch}}{COP_{vc}}\right) \tag{3.11}$$

Since F_{pgu} and Q_{ch} are positive values, the terms that go with them must be evaluated in order to define if ΔSEC increases or decreases.

For the term associated to F_{pgu} the analysis is as follow

$$\left[1-\eta_{pgu}\left(1-f_p\right)-\left(1-\eta_{pgu}\right)\frac{\eta_{rec}}{\eta_h}\right]=1-\frac{\eta_{rec}}{\eta_h}-\eta_{pgu}\left(1-f_p-\frac{\eta_{rec}}{\eta_h}\right)$$

The most favorable condition (value) of f_p, in order to obtain SEC reduction, is zero. Then

$$1-\frac{\eta_{rec}}{\eta_h}-\eta_{pgu}\left(1-f_p-\frac{\eta_{rec}}{\eta_h}\right)=\left(1-\frac{\eta_{rec}}{\eta_h}\right)-\eta_{pgu}\left(1-\frac{\eta_{rec}}{\eta_h}\right)=\left(1-\frac{\eta_{rec}}{\eta_h}\right)\left(1-\eta_{pgu}\right)$$

Since $\left(1-\eta_{pgu}\right)>0$, two cases derive from this equation

a) If $\eta_{rec}<\eta_h$, $\left(1-\frac{\eta_{rec}}{\eta_h}\right)>0$

b) If $\eta_{rec}>\eta_h$, $\left(1-\frac{\eta_{rec}}{\eta_h}\right)<0$

For the commercially available components for CHP system, it is considered that, $\eta_{rec}<\eta_h$. Therefore, Case (a) applies and the SEC will increase.

For the term associated to Q_{ch} the analysis is as follows

$\eta_h<1\Rightarrow\frac{1}{\eta_h}>1$, besides

$$COP_{ch} < COP_{vc} \Rightarrow \frac{COP_{ch}}{COP_{vc}} < 0 \text{, then } \left(\frac{1}{\eta_h} - \frac{COP_{ch}}{COP_{vc}}\right) > 0$$

The previous analysis of Equation (3.11) shows that the building-CHP system will increase the site energy consumption for the cooling, heating, and power operating condition.

Operating condition 2: Heating and power.

For this operating condition, the heat recovered is used to cover heating demands, $Q_{Ra} = Q_{rec}$. Then, the site energy consumption variation is defined as

$$\Delta SEC = F_{pgu}\left[1 - \eta_{pgu}\left(1 - f_p\right)\right] - \frac{Q_R}{\eta_h} \tag{3.12}$$

Using Equation (2.7), Equation (3.12) becomes

$$\Delta SEC = F_{pgu}\left[1 - \eta_{pgu}\left(1 - f_p\right)\right] - F_{pgu}\left(1 - \eta_{pgu}\right)\frac{\eta_{rec}}{\eta_h} \tag{3.13}$$

Rearranging Equation 3.13, it can be written as

$$\Delta SEC = F_{pgu}\left[1 - \frac{\eta_{rec}}{\eta_h} - \eta_{pgu}\left(1 - f_p - \frac{\eta_{rec}}{\eta_h}\right)\right] \tag{3.14}$$

Since F_{pgu} is a positive value, the term that goes with it must be evaluated in order to define if ΔSEC increases or decreases.

Similarly to the previous case, the most favorable condition (value) of f_p, in order to obtain SEC reduction, is zero. Then

$$\left[1 - \frac{\eta_{rec}}{\eta_h} - \eta_{pgu}\left(1 - f_p - \frac{\eta_{rec}}{\eta_h}\right)\right] = \left(1 - \frac{\eta_{rec}}{\eta_h}\right) - \eta_{pgu}\left(1 - \frac{\eta_{rec}}{\eta_h}\right)$$

Two cases are derived from this equation:

a) If $\eta_{rec} < \eta_h$, $\left(1 - \frac{\eta_{rec}}{\eta_h}\right) > 0$

b) If $\eta_{rec} > \eta_h$, $\left(1 - \frac{\eta_{rec}}{\eta_h}\right) < 0$

As mentioned before, for the commercially available components for CHP system, it is considered that, $\eta_{rec} < \eta_h$. Therefore, Case (a) applies and $\left(1 - \frac{\eta_{rec}}{\eta_h}\right) - \eta_{pgu}\left(1 - \frac{\eta_{rec}}{\eta_h}\right) > 0$.

The previous analysis of Equation (3.14) shows that the building-CHP system will increase the site energy consumption for the heating and power operating condition. The analysis was performed based on $Q_{Ra} = Q_{rec}$ which is the most favorable condition to utilize the recovered energy in order to reduce site energy consumption. Therefore, when $Q_{Ra} < Q_R$ the site energy consumption could be increased even more.

Operating condition 3: Cooling and power.

For this operating condition, two cases arise depending on if the boiler must supply additional heat in order for the absorption chiller to handle the cooling load.

Case 3.1: The recovered thermal energy supplies the heat required by the absorption chiller to handle the cooling load, $Q_{ch} = Q_R$. This implies that $Q_{Ra} = 0$ and $F_b = 0$. Thus, substituting Equation (2.7) in Equation (3.9), the site energy consumption variation is defined as

$$\Delta SEC = F_{pgu}\left[1 - \eta_{pgu}\left(1 - f_p\right)\right] - \frac{COP_{ch}}{COP_{vc}} F_{pgu}\left(1 - \eta_{pgu}\right)\eta_{rec} \tag{3.15}$$

Equation (3.15) can be rewritten as

$$\Delta SEC = F_{pgu}\left[1-\eta_{pgu}\left(1-f_p+\frac{COP_{ch}}{COP_{vc}}\frac{\eta_{rec}}{\eta_{pgu}}-\frac{COP_{ch}}{COP_{vc}}\eta_{rec}\right)\right] \tag{3.16}$$

Since F_{pgu} is a positive value, the term that goes with it must be evaluated in order to define if ΔSEC increases or decreases.

For the most favorable operating condition to reduce SEC, the following values apply:

$\eta_{rec}=1$, $f_p=0$, and $\frac{COP_{ch}}{COP_{vc}}=1$. Then,

$$\left[1-\eta_{pgu}\left(1-f_p+\frac{COP_{ch}}{COP_{vc}}\frac{\eta_{rec}}{\eta_{pgu}}-\frac{COP_{ch}}{COP_{vc}}\eta_{rec}\right)\right]>\left[1-\eta_{pgu}\left(1+\frac{1}{\eta_{pgu}}-1\right)\right]=1$$

The analysis of Equation (3.16) shows that the building-CHP system will increase the site energy consumption for the Case 3.1 of the cooling and power operating condition.

Case 3.2: The recovered heat is lower than the heat required by the absorption chiller to handle the cooling load, then $Q_{Ra}=0$ and $F_b \neq 0$. This case is explained by comparing it with Case 3.1. For Case 3.1, $F_b=0$ and the building-CHP system increases the site energy consumption, but for Case 3.2 $F_b \neq 0$ which implies more fuel consumption and consequent increase in site energy consumption.

3.2.2. CHP System Simulation: Site Energy Consumption

Table 3.2 and 3.3 present the SEC for the cases of CHP and CHP-BPER, respectively. Figure 3.1 and 3.2 illustrate the variation of the SEC for the cases of CHP and CHP-BPER, respectively. When the results are presented as percentage of variation, positive and negative values means more or less energy consumption with respect to the reference value (actual building SEC).

The results show the increment on SEC from the use of CHP systems. The increment occurs for all the cities and PGU efficiencies. For the case when the CHP system runs under the BPER operational strategy, the SEC can be reduced compared with the case without the BPER operational strategy. Based on the conditions of this study, the results presented in Figure 3.1 and 3.2 illustrate that if the CHP system operates under the BPER strategy the increment on the SEC can be reduced as much as 19.1%, 6.4%, 9.4%, 27.2%, and 5.4%, for Denver, Chicago, Sterling, San Francisco, and Tampa, respectively. Since economic evaluation is computed based on site energy prices, these results suggest that less energy cost should be achieved when BPER operational strategy is implemented.

Table 3.2 Site Energy Consumption for CHP System without BPER Strategy

	PGU	Site Energy Consumption (kWh)		
City/Zone	Efficiency	Building	CHP	Variation %
Denver Zone 1	0.25	511766	620129	21.2
	0.30		791451	54.7
	0.35		763929	49.3
Chicago Zone 2	0.25	587123	685414	16.7
	0.30		844171	43.8
	0.35		821177	39.9
Sterling Zone 3	0.25	494217	609140	23.3
	0.30		788825	59.6
	0.35		767962	55.4
San Francisco Zone 4	0.25	290703	370339	27.4
	0.30		499600	71.9
	0.35		548166	88.6
Tampa Zone 5	0.25	303476	497609	64.0
	0.30		544835	79.5
	0.35		738664	143.4

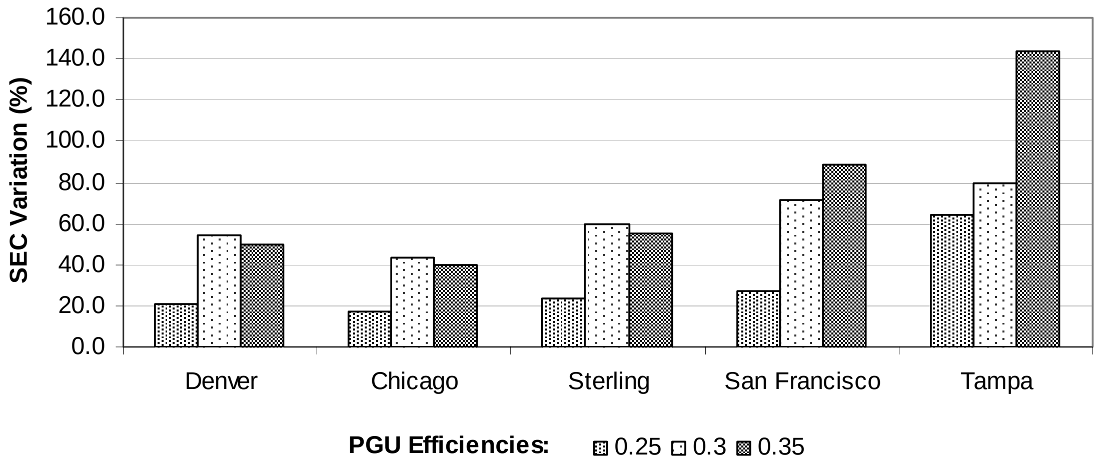


Figure 3.1 SEC Variation for CHP System without BPER Strategy

Table 3.3 Site Energy Consumption for CHP System with BPER Strategy

	PGU	Site Energy Consumption (kWh)		
City/Zone	Efficiency	Building	CHP-BPER	Variation %
Denver Zone 1	0.25	511766	594782	16.2
	0.30		738815	44.4
	0.35		763929	49.3
Chicago Zone 2	0.25	587123	666525	13.5
	0.30		804218	37.0
	0.35		821177	39.9
Sterling Zone 3	0.25	494217	586987	18.8
	0.30		742273	50.2
	0.35		767962	55.4
San Francisco Zone 4	0.25	290703	336252	15.7
	0.30		420636	44.7
	0.35		548166	88.6
Tampa Zone 5	0.25	303476	481871	58.8
	0.30		528591	74.2
	0.35		738664	143.4

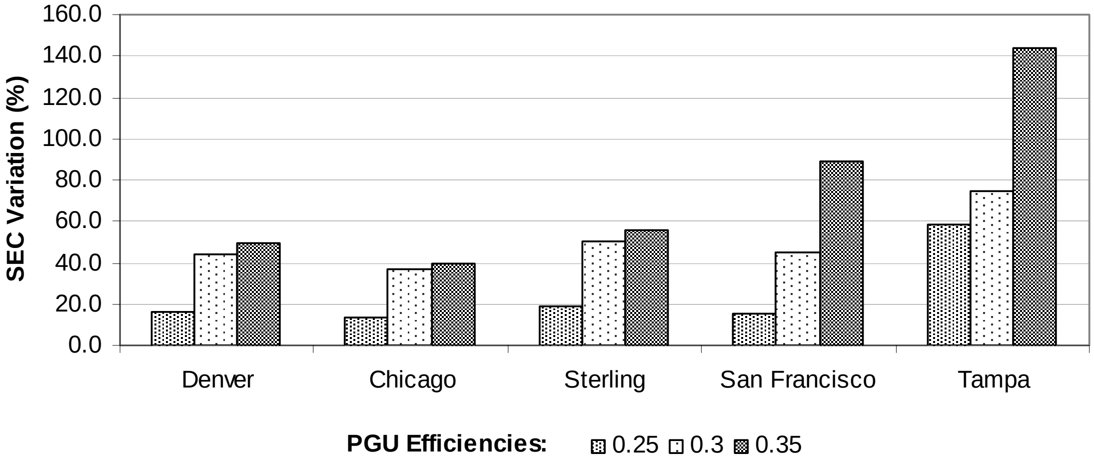


Figure 3.2 SEC Variation for CHP System with BPER Strategy

3.3 CHP SYSTEM EFFICIENCY

For any energy system, efficiency is a way to determine how much energy in the required form is generated, added, or removed from the system for a given input. Energy conservation efficiency for the CHP system sketched in Figure 2.2 can be written as

$$\eta_{chp} = \frac{\left(E_{pgu} - E_{p,chp}\right) + \left(Q_{ch} \cdot COP_{ch}\right) + \dfrac{Q_{Ra}}{\eta_h}}{F_{pgu} + F_b} \tag{3.17}$$

where the term ($Q_{ch} \cdot COP_{ch}$) corresponds to the cooling load handled by the absorption chiller.

Since CHP system increases the site energy consumption, it seems that the use of the first law efficiency alone is not appropriate to evaluate the energy performance of CHP systems. A similar statement was proposed by Zogg [12] "…some CHP promoters report "total efficiency" of CHP systems based on a first-law definition that simply sums electric and thermal outputs. Meaningful efficiency definitions, however, account for the relative values of the electric and thermal outputs." Therefore, an evaluation of CHP systems based on primary energy consumption, such as BPER, would be more adequate.

Examples of the false impression that could be derived from the use of the first law efficiency are presented in Figures 3.3 to 3.5. The figures show the comparison of the CHP system efficiency and the BPER. Figures 3.3, 3.4, and 3.5 show the results for the city of Chicago on October 21st, April 21st, and December 27th, respectively. In these figures values of zero efficiency implies that the CHP system is not operating, and consequently the BPER is 1.

Figure 3.3 illustrates that the CHP system performance based on BPER can follow the CHP system efficiency. Logically, better the efficiency better is the energy performance. However, Figure 3.4 and 3.5 illustrates that BPER as a measure of the CHP system energy performance does not necessarily follows the efficiency. As an example consider the two particular points at 3:00 p.m. (hour 15) in Figure 3.4, and at 10:00 p.m. (hour 22) in Figure 3.5. In the first point the BPER decreases while the efficiency increases, but in the second point the BPER increases while the efficiency decreases. Therefore, CHP system efficiency is not used in this study to evaluate the system energy performance.

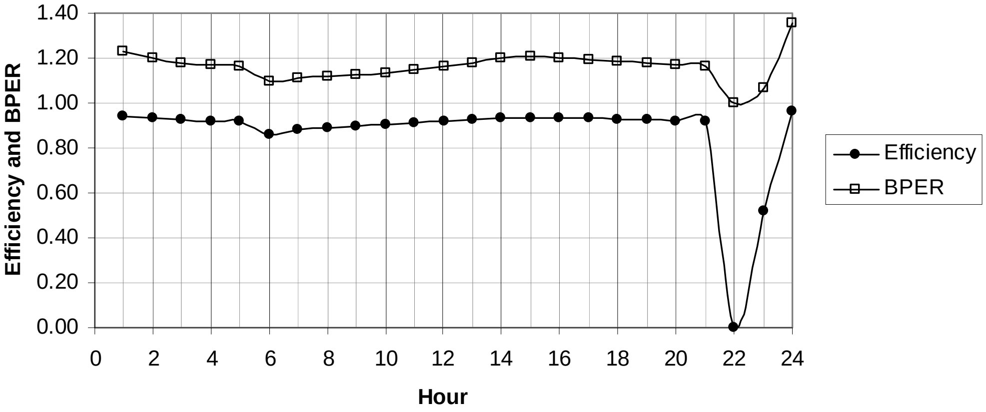


Figure 3.3 CHP System Efficiency and BPER for Chicago (IL) on October 21st

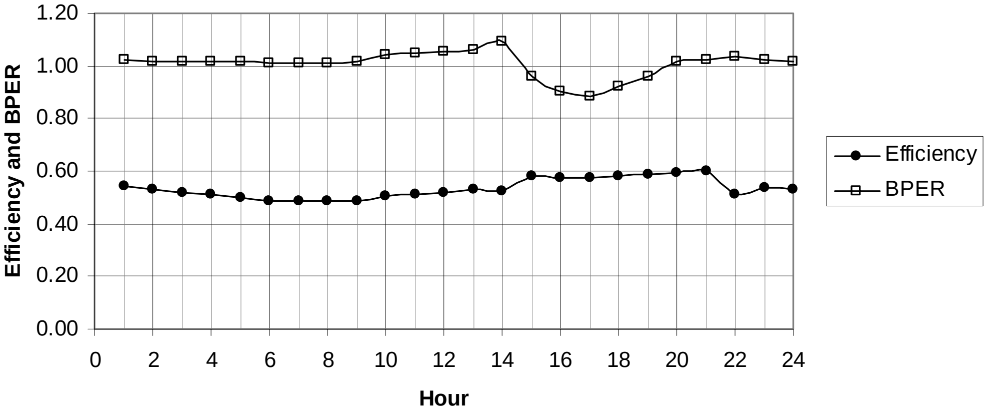


Figure 3.4 CHP System Efficiency and BPER for Chicago (IL) on April 21st

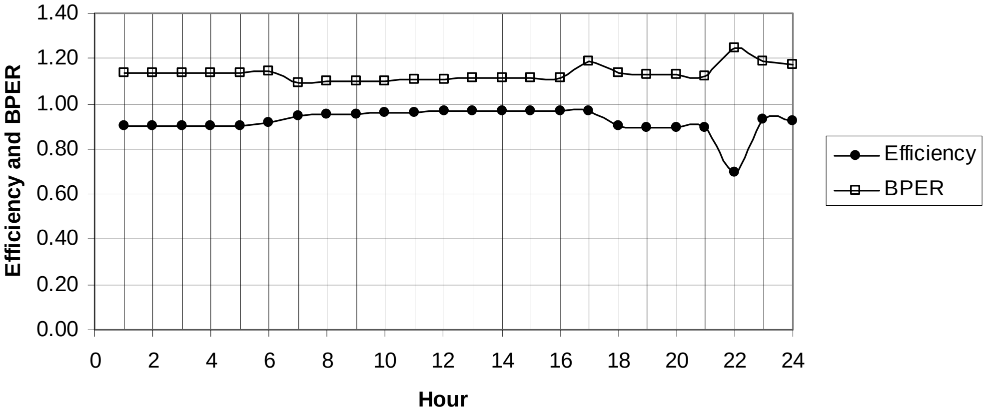


Figure 3.5 CHP System Efficiency and BPER for Chicago (IL) on December 27th

3.4 PRIMARY ENERGY CONSUMPTION

Table 3.4 presents the building primary energy consumption for the cities and PGU efficiencies considered in this study. The results show that for the best energy performance design (Table 3.1), CHP systems decrease the PEC for all cases. The lowest reduction, 2.3%, occurs for Tampa; and the highest reduction, 16.5%, occurs for Chicago.

Table 3.4 CHP System Primary Energy Consumption

	PGU	Primary Energy Consumption (kWh)		
City/Zone	Efficiency	Building	CHP	Variation %
Denver Zone 1	0.25	1006639	954584	-5.2
	0.30		916336	-9.0
	0.35		851704	-15.4
Chicago Zone 2	0.25	1093141	1030020	-5.8
	0.30		975374	-10.8
	0.35		912650	-16.5
Sterling Zone 3	0.25	1016587	961855	-5.4
	0.30		923577	-9.1
	0.35		858174	-15.6
San Francisco Zone 4	0.25	718772	696790	-3.1
	0.30		675979	-6.0
	0.35		614689	-14.5
Tampa Zone 5	0.25	960771	938926	-2.3
	0.30		899242	-6.4
	0.35		836461	-12.9

Table 3.4 demonstrates that for the same PGU efficiency different PEC variations are obtained, which verifies the influence of the building energy consumption profiles on the CHP energy performance. This table also shows that the incremental decrease of the PEC variation is higher for the efficiencies between 0.30 and 0.35 than for the efficiencies of 0.25 and 0.30. This can be explained because a PGU efficiency of 0.35 is higher than the efficiency (generation – transmission – distribution) for the utility power

plant which for this study is 0.30 obtained as the inverse of the ECF (1/3.343). Logically, when the PGU efficiency is higher than the power plant efficiency, even if the waste thermal energy is not recovered, better energy performance is achieved.

3.5 PRIMARY ENERGY CONSUMPTION FOR BPER STRATEGY

For the cities and PGU efficiencies considered in this study, Table 3.5 shows the building primary energy consumption for BPER operational strategy, while Figures 3.6 to 3.8 illustrate the variation in the PEC.

Table 3.5 CHP System Primary Energy Consumption for BPER Strategy

	PGU	Primary Energy Consumption (kWh)		
City/Zone	Efficiency	Building	CHP-BPER	Variation %
Denver Zone 1	0.25	1006639	948096	-5.8
	0.30		913236	-9.3
	0.35		851704	-15.4
Chicago Zone 2	0.25	1093141	1025099	-6.2
	0.30		973033	-11.0
	0.35		912650	-16.5
Sterling Zone 3	0.25	1016587	956181	-5.9
	0.30		920910	-9.4
	0.35		858174	-15.6
San Francisco Zone 4	0.25	718772	687412	-4.4
	0.30		671139	-6.6
	0.35		614689	-14.5
Tampa Zone 5	0.25	960771	934843	-2.7
	0.30		898208	-6.5
	0.35		836461	-12.9

Results in Table 3.5 are similar to those obtained for CHP systems running without the BPER operational strategy. However, Figures 3.6 and 3.7 illustrate that with the BPER operational strategy more PEC reduction can be achieved. As discussed in the previous section, the closeness of the PGU efficiency to the utility power plant efficiency has implications on the CHP system energy performance. When BPER operational strategy is applied, the benefits are more significant for lower PGU efficiencies. For higher PGU efficiencies, the results are the same when compared to the case without the BPER strategy as shown in Figure 3.8. When the PGU efficiency is higher than the utility power plant efficiency, better performance is obtained when the PGU operates. Therefore, the BPER operational strategy will not demand that the PGU stop, and consequently the results are the same.

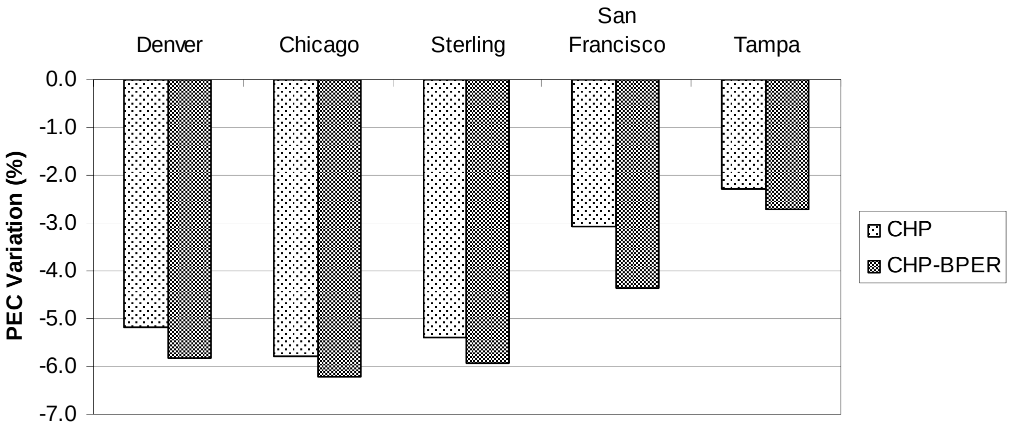


Figure 3.6 PEC Variation for CHP and CHP-BPER Cases, for $\eta_{pgu} = 0.25$

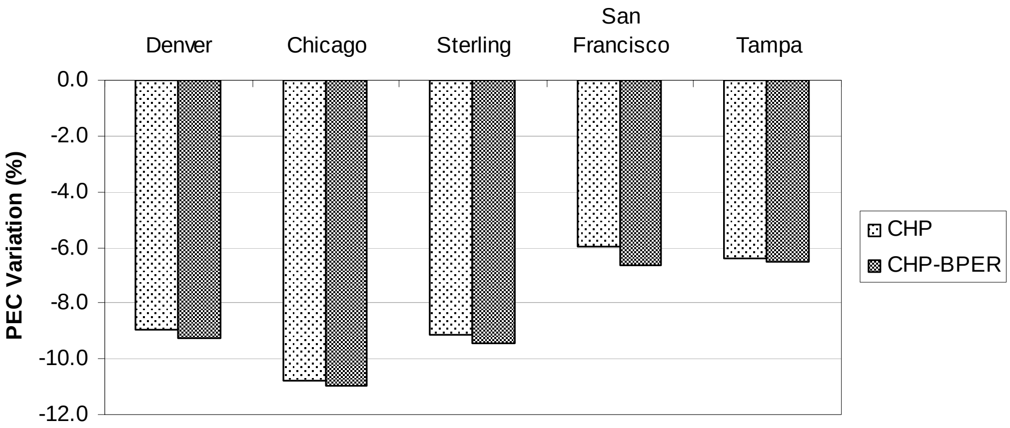


Figure 3.7 PEC Variation for CHP and CHP-BPER Cases, for $\eta_{pgu} = 0.30$

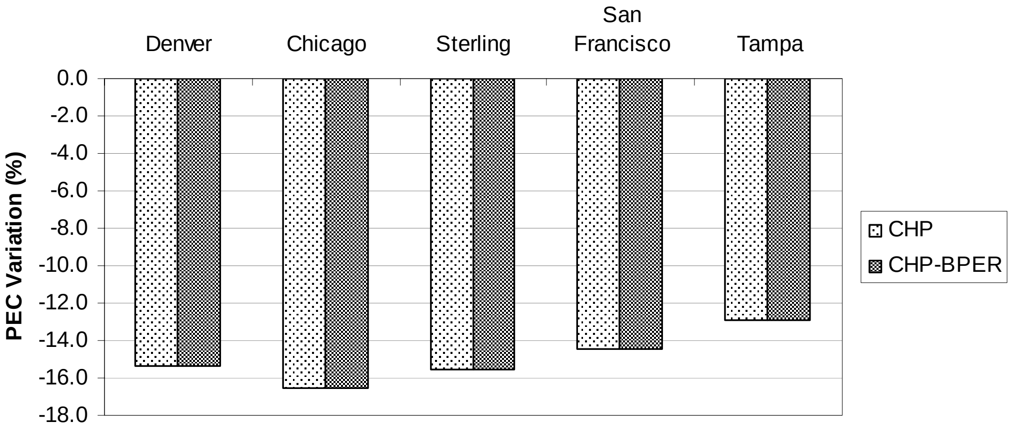


Figure 3.8 PEC Variation for CHP and CHP-BPER Cases, for $\eta_{pgu} = 0.35$

3.6 ECONOMIC CONSIDERATIONS

The results presented in this section correspond to those given by Target Finder [9] of the Energy Star program [8]. The site energy consumption for electricity and natural gas used in Target Finder are summarized in Appendix B. To better understand the results presented in this section, Table 3.6 show the estimated energy price used by Target Finder to compute the energy cost. For the PGU efficiencies considered in this study, Tables 3.7 and 3.8 present the energy cost for the cases when the CHP systems operates without and with the BPER operational strategy, respectively, while Figures 3.9 to 3.11 illustrate the variation in energy cost. The results confirm that CHP systems economic feasibility relies on energy price. This can be explained because as previously demonstrated, while increasing SEC, CHP system changes the building energy consumption profiles. Tables 3.7 and 3.8 show that for the cities of Sterling and Tampa, contrary to common belief, CHP systems increased energy cost. In general, with the exception of the city of San Francisco, Figures 3.9 and 3.10 show that with the BPER operational strategy better economic results can be obtained. However, even with the BPER operational strategy, as consequence of the variation in energy consumption profiles, for the cities of Chicago and Sterling, a peculiar case arises for the PGU efficiency of 0.30. For this PGU efficiency, the energy cost is higher than the cost for a PGU efficiency of 0.25. Figure 3.11 shows that for high PGU efficiency the energy cost is the same for the CHP and CHP-BPER. This is explained based on the same energy consumption for both cases at this PGU efficiency.

Table 3.6 Electricity and Natural Gas Price

	Price of Energy ($/kWh)[a]	
City	Electricity	Natural Gas
Denver	0.0670	0.0236
Chicago	0.0744	0.0293
Sterling	0.0588	0.0327
San Francisco	0.1188	0.0276
Tampa	0.0755	0.0375

a. Values obtained in January 2008

Table 3.7 CHP System Energy Cost

	PGU	Cost of Energy ($)		
City/Zone	Efficiency	Building	CHP	Variation %
Denver Zone 1	0.25	20969	20395	-2.7
	0.30		20318	-3.1
	0.35		18989	-9.4
Chicago Zone 2	0.25	26617	26241	-1.4
	0.30		26565	-0.2
	0.35		25132	-5.6
Sterling Zone 3	0.25	21843	23613	8.1
	0.30		26917	23.2
	0.35		25744	17.9
San Francisco Zone 4	0.25	24489	22504	-8.1
	0.30		19875	-18.8
	0.35		16770	-31.5
Tampa Zone 5	0.25	22026	25570	16.1
	0.30		25856	17.4
	0.35		28723	30.4

Table 3.8 CHP System Energy Cost for BPER Strategy

City/Zone	PGU Efficiency	Cost of Energy ($)		
		Building	CHP-BPER	Variation %
Denver Zone 1	0.25	20969	20395	-2.7
	0.30		20318	-3.1
	0.35		18989	-9.4
Chicago Zone 2	0.25	26617	25983	-2.4
	0.30		26168	-1.7
	0.35		25132	-5.6
Sterling Zone 3	0.25	21843	23084	5.7
	0.30		25920	18.7
	0.35		25744	17.9
San Francisco Zone 4	0.25	24489	22610	-7.7
	0.30		20784	-15.1
	0.35		16770	-31.5
Tampa Zone 5	0.25	22026	25187	14.4
	0.30		25514	15.8
	0.35		28723	30.4

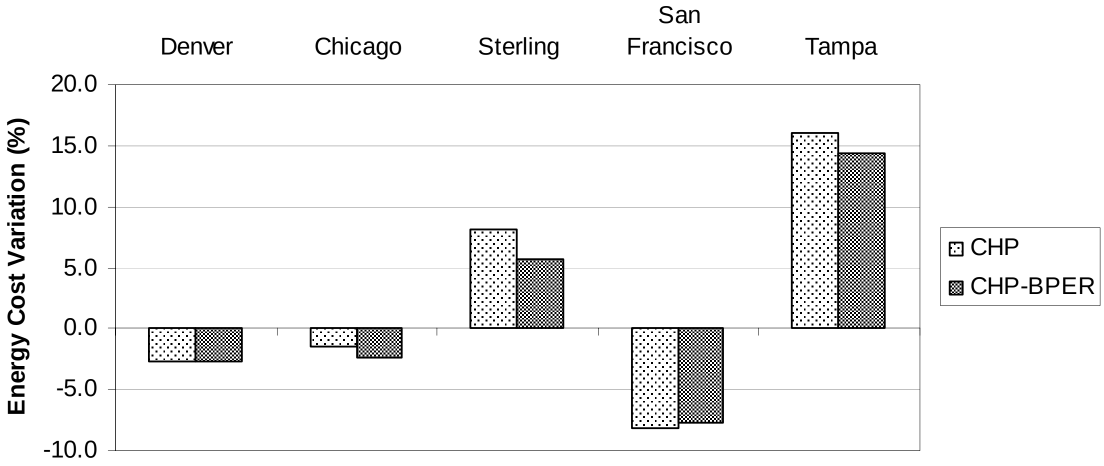


Figure 3.9 Energy Cost Variation for CHP and CHP-BPER Cases, for $\eta_{pgu} = 0.25$

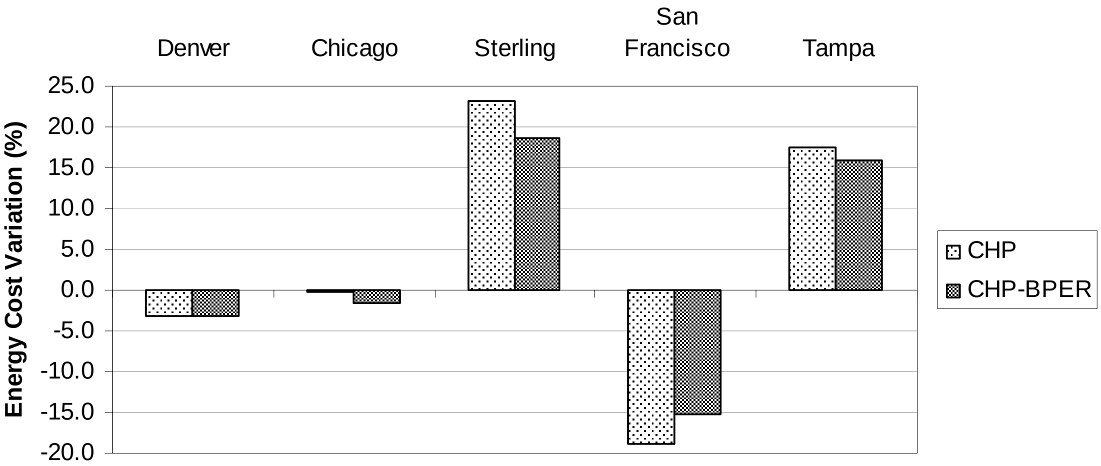


Figure 3.10 Energy Cost Variation for CHP and CHP-BPER Cases, for $\eta_{pgu} = 0.30$

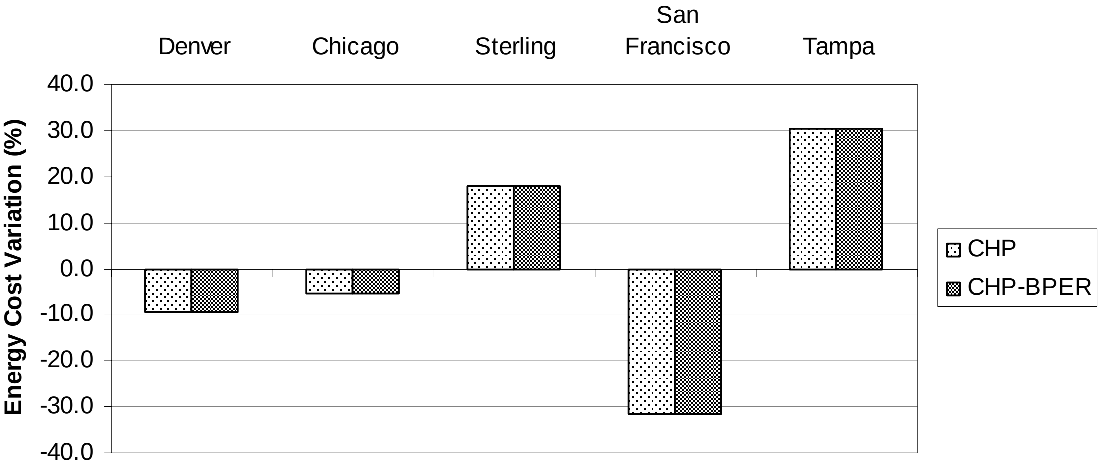


Figure 3.11 Energy Cost Variation for CHP and CHP-BPER Cases, for $\eta_{pgu} = 0.35$

3.6.1 Energy versus Economics

The main goal of the use of CHP systems is to reduce energy consumption, and to reduce emission of pollutants. One of the main topics that this study wants to show is the misconception that could be derived from the cost-oriented design of CHP system. Figures 3.12 and 3.13 are two examples comparing CHP system design based on primary energy consumption (PEC) and energy cost (EC). In these figures CHP Energy and

CHP-BPER are the results discussed in Sections 3.4 and 3.5, respectively. CHP Cost and CHP-ECR refer to the energy cost obtained from the lowest energy cost for the cases without and with the energy cost ratio (ECR) operational strategy, respectively. The results for the energy cost operational strategy were obtained by implementing the ECR factor in the simulation software. The ECR is defined as the ratio of the actual building site energy cost and the building-CHP system site energy cost. The ECR operational strategy is equivalent to the BPER operational strategy, but accounting for energy cost in lieu of energy consumption.

Figure 3.12 illustrates the variation of PEC and EC for the city of Chicago for a PGU efficiency of 0.30. This figure shows that the maximum PEC reduction of 11% is obtained with an energy cost reduction of 1.7% when the BPER operational strategy is used. However, the maximum energy cost reduction of 5.7% is obtained with a lower PEC reduction (8.2%) when the ECR operational strategy is used.

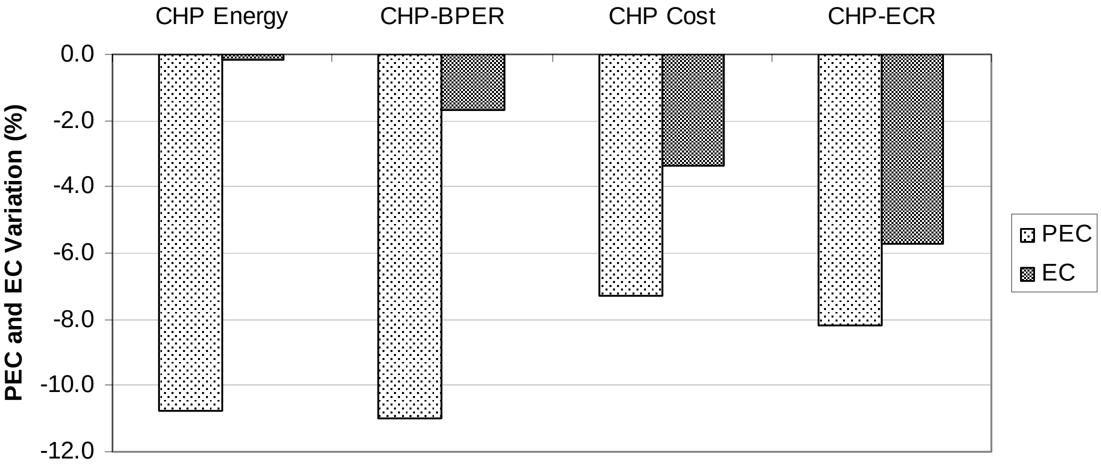


Figure 3.12 Variation of PEC and EC for the City of Chicago, $\eta_{pgu} = 0.30$

Similarly, Figure 3.13 illustrates the variation of PEC and EC for the city of San Francisco for a PGU efficiency of 0.25. For San Francisco, the maximum PEC reduction of 4.4% is obtained with an energy cost reduction of 7.7% when the BPER operational strategy is used. However, the maximum energy cost reduction of 12.4% is obtained with an increment of PEC of 1.8% when the ECR operational strategy is used. This analysis is more noticeable for the case when the CHP system operates without any operational strategy, shown as CHP Cost Case in Figure 3.13. An energy cost reduction of 12.4% is obtained which could justify the implementation of the CHP system, but with the contradictory result that the PEC would increase 10.2%.

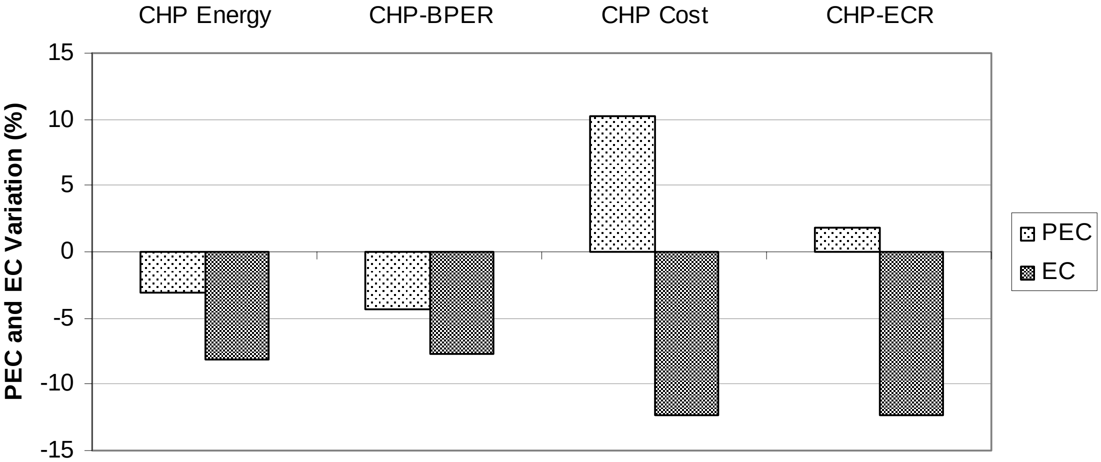


Figure 3.13 Variation of PEC and EC for the City of San Francisco, $\eta_{pgu} = 0.25$

Figure 3.14 illustrates the variation of PEC and EC for the city of Sterling for a PGU efficiency of 0.25. For Sterling, only when the CHP system operates with the ECR operational strategy the EC is reduced, Case shown in Figure 3.14 as CHP-ECR. The BPER operational strategy (Case CHP-BPER) gives the greatest PEC reduction of 5.9%, but with an increase of 5.7% in the EC. Comparing both cases, CHP-BPER and CHP-ECR, the difference in PEC reduction is only 1%, while the difference in EC is 7.9% (CHP-BPER increases the EC in 5.7% and CHP-ECR decreases the EC in 2.2%). This particular result suggests that in a tradeoff between EC and PEC, the ECR operational strategy could be a better option than the BPER operational strategy.

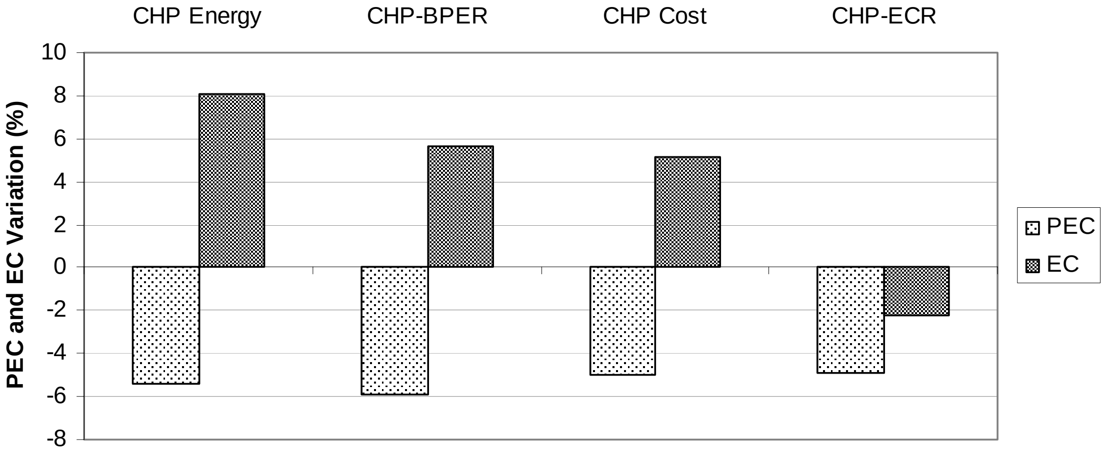


Figure 3.14 Variation of PEC and EC for the City of Sterling, $\eta_{pgu} = 0.25$

3.8 CONCLUSION

The use of CHP systems increase SEC and change the energy consumption profile, which leads to the conclusion that PEC should be used for the design of CHP systems. Since CHP system efficiency only considers the site energy input and output through the system components, it is not satisfactory to evaluate the system energy performance. Therefore, primary energy was used and validated as a satisfactory parameter to evaluate CHP system energy performance. The BPER operational strategy as tool to obtain the best energy performance design was validated. The use of the ECR operational strategy proved that a cost-oriented design could yield misleading results. For critical designs, high savings can be obtained with unacceptable increment of the PEC. Accordingly, to be in agreement with the concept of CHP system regarding reduction of energy consumption and emission of pollutants, CHP systems should be designed based on optimization of the primary energy consumption, and then economic analysis could be used for the final decision of implementing the system. The demonstration that CHP systems increase the SEC could help to understand and explain why sometimes CHP systems are not economically feasible in some markets. Besides, this also could help to investigate strategies and legislation that could guarantee economic savings with a simultaneous guarantee of energy savings.

CHAPTER IV

CHP SYSTEM ANALYSIS FOR MONTHLY ENERGY CONSUMPTION

4.1 INTRODUCTION

Most common energy consumption data available for consumers is on a monthly basis, generally obtained from utility bills. However, efficacy and efficiency of CHP systems rely on the match of electrical power and thermal energy demands. Since monthly energy consumption (MEC) does not say anything about the match (time and amount) between electric and thermal demands, CHP system analysis based on MEC could yield misleading results. Results presented in this section give an idea of the magnitude of error if a monthly analysis is made instead of an hourly analysis. By understanding the limitations of the CHP systems analysis based on monthly data, better judgment of the relevance of monthly analysis for a specific project can be made.

4.2 RESULTS FOR MONTHLY ENERGY CONSUMPTION ANALYSIS

The model for CHP system analysis based on MEC presented in Section 2.3 was used to obtain the results presented in this section. Table 4.1 and 4.2 present the variation of PEC and EC, respectively, for the cities and PGU efficiencies considered in this study. The variation is computed by comparing the results for PEC obtained from the monthly CHP system analysis and the monthly actual building PEC. Similar to previous tables, negative and positive values imply reduction and increment, respectively.

Table 4.1 Variation of PEC for CHP System Monthly Analysis

	PGU	Primary Energy Consumption (kWh)		
City/Zone	Efficiency	Building	CHP	Variation %
Denver Zone 1	0.25	1006638	785634	-22.0
	0.30		713932	-29.1
	0.35		676263	-32.8
Chicago Zone 2	0.25	1093141	854291	-21.8
	0.30		796368	-27.1
	0.35		754338	-31.0
Sterling Zone 3	0.25	1016587	799757	-21.3
	0.30		725863	-28.6
	0.35		684122	-32.7
San Francisco Zone 4	0.25	718772	628902	-12.5
	0.30		575546	-19.9
	0.35		496394	-30.9
Tampa Zone 5	0.25	960771	831603	-13.4
	0.30		742878	-22.7
	0.35		665110	-30.8

Table 4.2 Variation of Energy Cost for CHP System Monthly Analysis

	PGU	Energy Cost ($)		
City/Zone	Efficiency	Building	CHP	Variation %
Denver Zone 1	0.25	20969	17654	-15.8
	0.30		16080	-23.3
	0.35		15230	-27.4
Chicago Zone 2	0.25	26617	23942	-10.0
	0.30		22315	-16.2
	0.35		21139	-20.6
Sterling Zone 3	0.25	21843	24992	14.4
	0.30		22437	2.7
	0.35		21376	-2.1
San Francisco Zone 4	0.25	24489	19783	-19.2
	0.30		15856	-35.3
	0.35		13106	-46.5
Tampa Zone 5	0.25	22026	29639	34.6
	0.30		26562	20.6
	0.35		23794	8.0

As expected, Table 4.1 shows that a higher PGU efficiency yields higher reduction of PEC. This table also illustrates that the monthly analysis always yields higher PEC reduction (as much as 32.8% for the city of Denver). This can be explained by the fact that most of the recovered thermal energy can be utilized for heating and cooling although there is no matching with electric power. Similarly, Table 4.2 shows that CHP system utilization could yield a reduction of EC as much as 46% for the city of San Francisco, but also an increment of EC as much as 34% for the city of Tampa.

The results of PEC and EC with the monthly based analysis seem to exhibit a large discrepancy with the hourly based results. As reference for the magnitude of error, Tables 4.3 and 4.4 present the error for PEC and EC, respectively, that is obtained if the CHP system is analyzed based on MEC instead of hourly energy consumption.

Table 4.3 Comparison of PEC for Monthly and Hourly Analysis

	PGU	Primary Energy Consumption (kWh)		
City/Zone	Efficiency	Hourly	Monthly	Error %
Denver Zone 1	0.25	948096	785634	-17.1
	0.30	913236	713932	-21.8
	0.35	851704	676263	-20.6
Chicago Zone 2	0.25	1030020	854291	-17.1
	0.30	975374	796368	-18.4
	0.35	912650	754338	-17.3
Sterling Zone 3	0.25	956181	799757	-16.4
	0.30	920910	725863	-21.2
	0.35	858174	684122	-20.3
San Francisco Zone 4	0.25	687412	628902	-8.5
	0.30	671139	575546	-14.2
	0.35	614689	496394	-19.2
Tampa Zone 5	0.25	934843	831603	-11.0
	0.30	898208	742878	-17.3
	0.35	836461	665110	-20.5

Table 4.4 Comparison of Energy Cost for Monthly and Hourly Analysis

	PGU	Energy Cost ($)		
City/Zone	Efficiency	Hourly	Monthly	Error %
Denver Zone 1	0.25	20395	17654	-13.4
	0.30	20318	16080	-20.9
	0.35	18989	15230	-19.8
Chicago Zone 2	0.25	26241	23942	-8.8
	0.30	26565	22315	-16.0
	0.35	25132	21139	-15.9
Sterling Zone 3	0.25	23084	24992	8.3
	0.30	25920	22437	-13.4
	0.35	25744	21376	-17.0
San Francisco Zone 4	0.25	22610	19783	-12.5
	0.30	20784	15856	-23.7
	0.35	16770	13106	-21.8
Tampa Zone 5	0.25	25187	29639	17.7
	0.30	25514	26562	4.1
	0.35	28723	23794	-17.2

From Tables 4.3 and 4.4 it can be observed that the error can be as much as 21% and 23% for PEC and EC, respectively. However, for better visualization of the errors, Figures 4.1 to 4.3 illustrates the error for the PGU efficiencies considered in this study. As for previous tables, negative error means that the monthly analysis decreases the variable (PEC or EC) with respect to the hourly analysis, and positive values indicate increment of the variable with respect to the hourly analysis.

With the exception of San Francisco as consequence of the highest price of electricity, the results show that in general the reduction of PEC is higher than the reduction of EC for the monthly analysis. Regardless of which variable decreases more, in general a monthly analysis can turn an energetically and economically unfeasible system into a feasible one. On the other hand, a critical condition arises for low PGU efficiencies in some cities. For Sterling and Tampa at a PGU efficiency of 0.25, and for

Tampa at a PGU efficiency of 0.30, the PEC decreases while the EC increases. This condition can turn an energetically and economically feasible system into an economically unfeasible system.

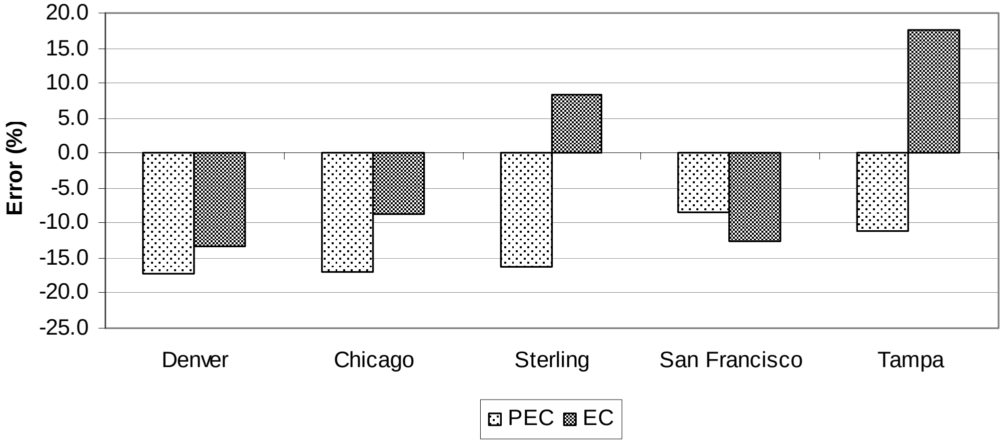


Figure 4.1 Error for the Monthly Analysis for $\eta_{pgu} = 0.25$

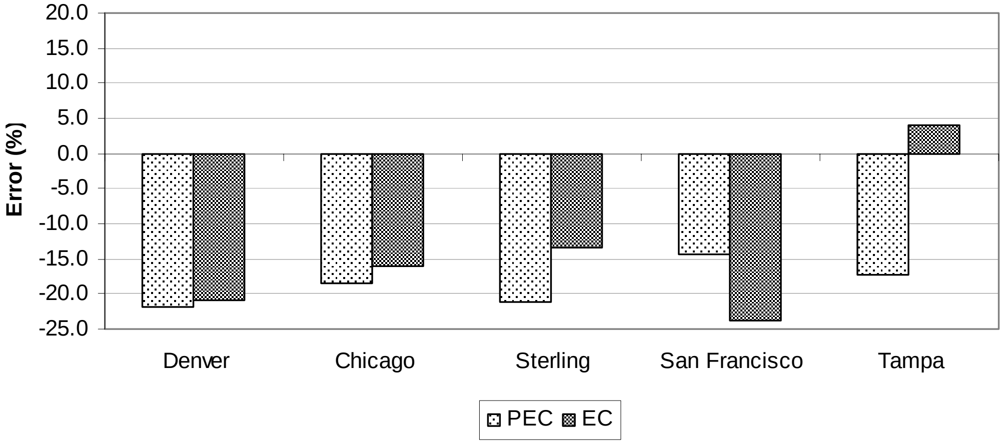


Figure 4.2 Error for the Monthly Analysis for $\eta_{pgu} = 0.30$

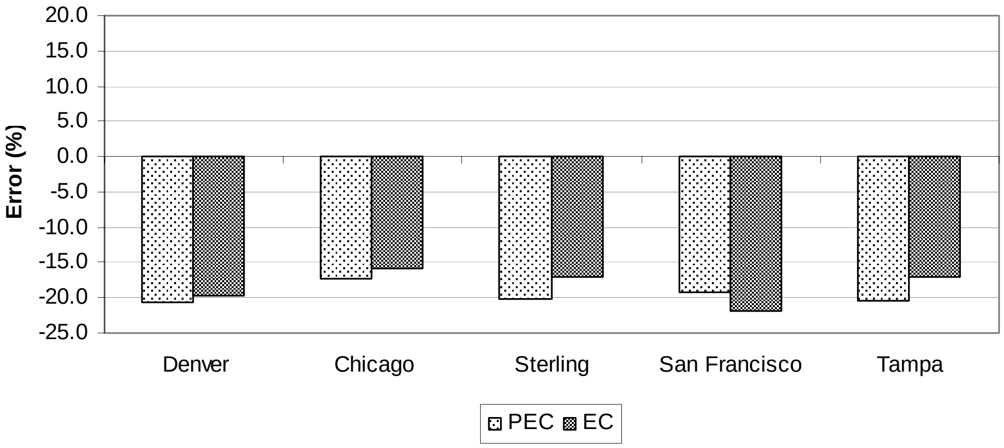


Figure 4.3 Error for the Monthly Analysis for $\eta_{pgu} = 0.35$

4.3 CONCLUSION

For the condition considered in this study, the error from a CHP simulation based on monthly analysis can be as much as 21.8% for primary energy consumption, and 23.7% for energy cost. For some cases the errors have different directions, which can let a design seem less feasible than what it actually is. For cases such as San Francisco, when the cost of electricity is too high, the project can be considered economically feasible while actually it is not. Then, the magnitude and direction of the errors could yield misinterpretation of the feasibility of a CHP system project. Because of the availability of monthly energy consumption and cost, a first approximation of CHP system feasibility based on monthly information is useful, but further research is required in order to develop a methodology that allows improving the estimation of CHP system performance from monthly energy consumption data.

CHAPTER V

NON CONVENTIONAL EVALUATION OF CHP SYSTEMS

5.1 INTRODUCTION

Several researchers have investigated and reported the economic benefits of using CHP systems such as Newborough [24], Keppo and Savola [25], Jablko et al., [26], Tucker [27], De Paepe et al. [28], Zoog [29], and Mago et al., [30]. Although most of the time CHP technology seems to be economically feasible, results from Chapter III show that CHP system can not always guarantee economic savings. However, a well designed CHP system can guarantee energy reduction, which makes necessary the quantification of other benefits from this technology in order to offset any economic weakness that can arise as consequence of energy prices.

A non-conventional evaluation of CHP systems, based on non-economical aspects, will show the additional benefits that can be obtained from this technology. As customers, investors, and government continue to be more involved and to develop more understanding about energy choices, a non-conventional evaluation seems to be the solution to offset economic weakness of CHP systems. Besides, as conservation of energy resources and reduction of emissions are guaranteed by CHP technology, economic barriers can be offset through legislation or economic incentives as those given to promote renewable energy technologies.

Some aspects that could be included in a non-conventional evaluation are: building energy rating, emission of pollutants, power reliability, power quality, fuel source flexibility, brand and marketing benefits, protection from electric rate hikes, and benefits from promoting energy management practices. Some of these suggested benefits from a non-conventional evaluation can be factored into an economic evaluation but others would give intangible potential to the technology. This study, for a non-conventional evaluation of CHP systems, focuses on building energy rating and reduction of emissions because both of them are directly related to the CHP energy performance.

5.2 BUILDING ENERGY RATINGS

Two building energy ratings are recognized for benchmarking buildings in the U.S.A., Energy Star and Leadership in Energy and Environmental Design (LEED). The methodology to evaluate CHP systems based on Energy Star Rating is described in Section 5.2.1. For LEED Rating there is one for new constructions (LEED-NC Rating), and other one for existing buildings (LEED-EB Rating). The methodology presented in section 5.2.2 is described based on the LEED-EB Rating, but can also be applied to the LEED-NC.

5.2.1 Methodology to Determine the Energy Star Rating

CHP systems can improve the energy performance of a building, which can be evaluated using the Energy Star Rating. Energy Star program [8] focuses on homes and business. Energy Star program offers energy management strategies and tools that help to improve and track energy performance for commercial buildings. To assess energy performance for design projects and major building renovations, the program offers a web-based tool called Target Finder [9]. This tool rates the level of energy performance of a building on a 100 scale. To estimate how much energy a building would use at each level of performance, statistical analysis on the data gathered by the Department of Energy's Energy Information Administration is used by the tool. A building achieving a rating of 75 or higher and with a healthy and productive indoor air environment, consistent with industry standards, is eligible to receive the Energy Star label. According to the program, displaying an ENERGY STAR plaque conveys superior performance to tenants, customers, and employees. The building actual source energy data are weather normalized, which allows assessing the building performance relative to the typical weather for the corresponding region. As a national program for protecting the environment through superior energy efficiency, Energy Star uses source energy as the basis for benchmarking commercial building energy performance.

Target Finder requires building information to perform the rating. The required information is explained in Steps 1 through 4. In the last step, Step 5, the Energy Star Rating of the actual building energy performance can be compared with the energy performance when a CHP system is used. The steps required to determine the rating using Target Finder are described below:

1. *Facility Information:* Complete the following information required by Target Finder: Zip Code, Facility Name, City, and State. The Zip Code is used to determine the climate conditions that the building would experience in a normal year and to estimate how much energy is used at the source according with the energy fuel mix typical in the region specified by the zip code.

2. *Facility Characteristics:* Complete the information required by Target Finder related to the space type, which can be classified as Primary Space Type and Secondary Space Type. For each space type general information is required. For example, for general offices the tool requires the gross floor area, operating hours/week, workers on main shift, number of PCs, percentage of the office with air-conditioning, and percentage of the office heated.

3. *The Target:* Another input required by Target Finder is to define a "Target Rating" or "Energy Reduction Target". For this methodology any option will not affect the result, but it is recommended to use a target rating of 50%.

4. *Estimated Design Energy:* The annual energy consumption must be introduced in this section. The tool allows accounting for two types of energy sources. The energy sources considered by the tool are: electricity, natural gas, fuel oil (No. 1), fuel oil (No. 2), fuel oil (No. 4), fuel oil (No. 5 and No. 6), steam, chilled water, wood, propane, liquid propane, kerosene, diesel (No. 2), coal (anthracite), coal (bituminous), and coke. A menu with appropriate units is available for each energy source.

5. *Comparing Rating:* The tool must be run with the same data for the "Facility Information" and the "Facility Characteristics", but the "Estimated Design Energy" must account for the variation of the annual energy consumption without and with the CHP system. The Energy Star Rating is found first with the actual building energy consumption and then with the estimated annual energy consumption obtained with the

model described in Chapter II. The variation in the rating (points) will give the benefits of CHP systems in the Energy Star Rating.

5.2.2 Methodology to Determine the LEED-EB Rating

If energy efficiency is the primary goal, the Energy Star certification can be achieved using CHP systems. When other aspects such as sustainability are of interest, CHP systems can be important contributors to achieve a Leadership in Energy and Environmental Design (LEED) certification. Complete information about the LEED Green Building Rating System can be found in [31]. To achieve LEED certification, buildings must meet all prerequisites in the Rating System and a minimum of 32 points. LEED for Existing Buildings (LEED-EB) Rating is awarded according to the following point thresholds: Certified 34–42 points, Silver 43–50 points, Gold 51–67 points, and Platinum 68–92 points [32]. The categories that are evaluated and the respective possible points are: Sustainable Sites (12 points), Water Efficiency (10 points), Energy and Atmosphere (30 points), Materials and Resources (14 points), Indoor Environmental Quality (19 points), and Innovation in Operations (7 points). For the Energy and Atmosphere category, Credit 1 – Optimize Energy Performance has the greater weight with 15 points and is based on Energy Star Rating according with Table 5.1. An Energy Star score of 67 points achieves 1 LEED-EB point and increases up to 15 LEED-EB points for a score of 95^+ on the Energy Star scale.

Table 5.1 Points for the LEED-EB Rating from Energy Star Rating

Energy Star Rating	LEED-EB Points
67	1
69	2
71	3
73	4
75	5
77	6
79	7
81	8
83	9
85	10
87	11
89	12
91	13
93	14
95^+	15

Adapted from [32]

To evaluate the contribution of CHP systems in the Energy and Atmosphere category of the LEED-EB Rating the following steps are recommended:

1. *LEED-EB Points from Credit 1:* To estimate the points that can be attain from Credit 1 – Optimize Energy Performance, the steps of the Energy Star Rating must be followed to obtain the score and then use Table 5.1 to define the points that can be gained.

2. *LEED-EB Points from Credit 5:* The absorption chiller uses no ozone depleting fluorocarbons in concordance with Credit 5 – Refrigerant Management. Once the CHP system has been designed, point from Credit 5 could be gained. However, if the design requires the use of vapor compression systems, the methodology on the Option B of Credit 5 [32] must be followed in order to define if the point from this credit is gained.

3. *LEED-EB Points from Credit 6:* The methodology to estimate the reduction of emission of pollutants described in the next section can be used to define if the point from Credit 6 – Emissions Reduction Reporting can be gained. This credit requires quantifying and reporting the reductions, which can be done by the methodology proposed.

4. *Compare the LEED-EB Points:* Once the LEED-EB points have been estimated for the actual building and the building-CHP system, the variation on the numbers of points will give the contribution of the use of CHP systems on the LEED-EB Rating.

5.3 EMISSION OF POLLUTANTS METHODOLOGY

To estimate reduction of emission of pollutants from the use of CHP systems, the energy consumption is used to estimate the amount of pollutants by using emission factors. Emission factors account for the average emission rate of pollutants based on the energy obtained from burning fuels. The pollutants considered in this methodology are nitrogen oxides (NO_x), sulfur dioxide (SO_2), and carbon dioxide (CO_2). Although other pollutants could be obtained from the combustion process of fossil fuels, for simplification purposes this methodology only consider the pollutants evaluated by the DOE tool Power Profiler [33] used to estimate the emission of pollutants from the electric energy use. The steps required to determine the reduction of pollutants from the use of CHP systems are described below:

1. *Energy Consumption:* Define the actual building energy consumption (related to the site energy) and the estimated building energy consumption when a CHP system is used.

2. *Emissions from Electricity:* For electricity, pollutants are estimated by means of the emission factors used internally by the Web-based tool Power Profiler [33]. This tool allows users to determine specific impacts of air emissions associated with their consumption of electricity based on the actual monthly use or average monthly use. This tool requires a Zip Code to show the electric distribution utilities in that region grid, and estimates the emissions based on the fuel mix used to generate electricity in that region. The results given by Power Profiler include an adjustment of 9 percent for line losses. To find the emission of CO_2, NO_x, and SO_2, Power Profiler must be run for the building actual energy consumption and for the building energy consumption when a CHP system is used.

3. *Emissions from Fuels:* Different emission factors are required for each different fuel. This study focuses only on natural gas. Therefore, pollutants are estimated using the emission factors presented in Table 5.2 obtained from data for natural gas published by the Energy Information Administration [34]. However, the same methodology can be applied for different fuels using the corresponding emission factors.

4. *Reduction of Emission of Pollutants:* The total emission of pollutants is estimated by considering all the emission from all the energy sources used in the building. The total emission of pollutants must be determined for each case, without and with the use of CHP system. Once the total emissions have been estimated, the reduction is computed by the difference.

Table 5.2 Natural Gas Emission Factors

Pollutant	kg/MWh
Carbon Dioxide (CO_2)	181.1
Nitrogen Oxides (NO_x)	0.1424
Sulfur Dioxide (SO_2)	0.0015

5.4 RESULTS FOR NON-CONVENTIONAL EVALUATION

Based on the energy consumption results obtained in Chapter III, and applying the methodology for non conventional evaluation described previously, Sections 5.4.1 and 5.4.2 present the results for the energy ratings and emission of pollutants, respectively. As mentioned previously, the results are presented for offices in the cities and PGU efficiencies considered in this study. Since the methodology for energy rating and emission of pollutants requires the type of energy source, Appendix B presents the site energy consumption for electricity and natural gas obtained from the simulations of CHP systems.

5.4.1 Energy Ratings, Energy Star and LEED-EB

Tables 5.3 and 5.4 present the Energy Star Rating and the points for the LEED-EB Rating, respectively. The points for the LEED-EB only consider the points that can be gain from Credit 1. Figure 5.1 illustrates the increment of the Energy Star Rating from the use of CHP Systems.

Table 5.3 shows that CHP systems increase the Energy Star rating. However, the Energy Star Rating is the same when the CHP system operates without and with the BPER operational strategy. This means that the incremental decrease of energy consumption from the use of the BPER operational strategy is not enough to further improve the Energy Star Rating.

Figure 5.1 illustrates that CHP systems increases the Energy Star Rating for all cities. The greatest incremental increase is 16 for city of Chicago, while the lowest incremental increase is 3 for the cities of San Francisco and Tampa. As expected, higher PGU efficiency implies less energy consumption and consequently higher Energy Star Rating.

Table 5.4 shows that points from Credit 1 for the LEED-EB Rating can not be obtained for all evaluated cities. This is explained because the Energy Star Rating without the CHP system is too low. For the conditions of this study the greatest incremental increase was 4 points for the city of San Francisco, which represents 27% of the total 15 points that can be gained.

Table 5.3 Energy Star Rating

	PGU	Energy Star Rating		
City/Zone	Efficiency	Building	CHP	CHP-BPER
Denver Zone 1	0.25	56	61	61
	0.30		64	65
	0.35		70	70
Chicago Zone 2	0.25	49	55	55
	0.30		59	60
	0.35		65	65
Sterling Zone 3	0.25	54	59	59
	0.30		62	62
	0.35		68	68
San Francisco Zone 4	0.25	74	76	77
	0.30		78	78
	0.35		83	83
Tampa Zone 5	0.25	58	60	61
	0.30		64	64
	0.35		70	70

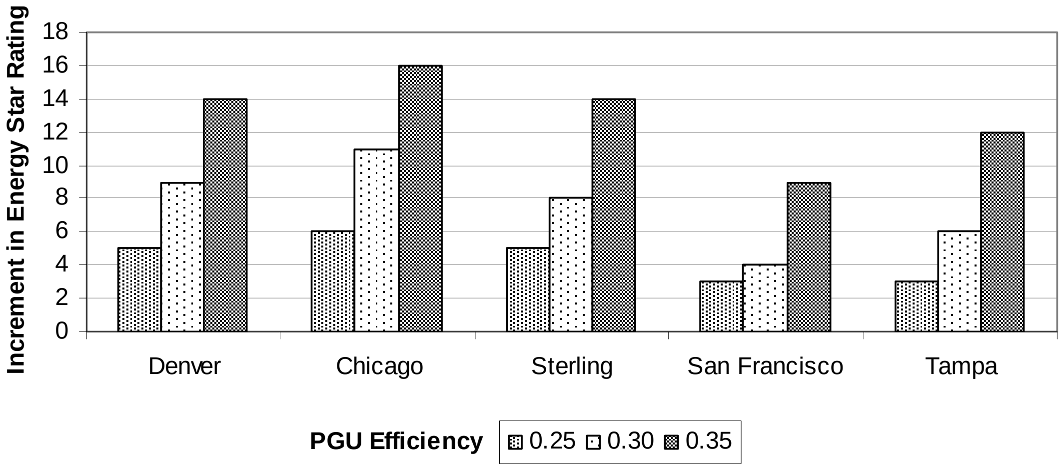


Figure 5.1 Increment of Energy Star Rating from the Use of CHP Systems

Table 5.4 LEED-EB Rating Points from Credit 1

	PGU	LEED-EB Credit 1 Points		
City/Zone	Efficiency	Building	CHP	CHP-BPER
Denver Zone 1	0.25	0	0	0
	0.30		0	0
	0.35		2	2
Chicago Zone 2	0.25	0	0	0
	0.30		0	0
	0.35		0	0
Sterling Zone 3	0.25	0	0	0
	0.30		0	0
	0.35		2	2
San Francisco Zone 4	0.25	5	5	6
	0.30		6	6
	0.35		9	9
Tampa Zone 5	0.25	0	0	0
	0.30		0	0
	0.35		2	2

5.4.2 Emission of Pollutants

Emission factor for electricity depends on the fuel mix used to generate electricity in the region where the energy has been used. To better understand the results of this section, Appendix C describes the effect of the fuel mix for the electric grid regions associated to the cities considered in this study.

For CHP systems, Tables 5.5, 5.6, and 5.7 present the estimated emission of Nitrogen Oxides (NO_x), Sulfur Dioxide (SO_2), and Carbon Dioxide (CO_2), respectively. Figures 5.2, 5.3, and 5.4 illustrate the percentage of reduction for NO_x, SO_2, and CO_2, respectively. For all the cases considered, CHP systems reduce the emission of pollutants, and high PGU efficiency has a significant impact on emission reductions.

Figure 5.2 shows that NO_x can be reduced as much as 75% for the cities of Denver and Tampa, with a minimum of 11% for the city of San Francisco. Figure 5.3 shows that SO_2 can be reduced as much as 90% for all the cities, with a minimum of 19% for the city of San Francisco. Figure 5.4 shows that CO_2 can be reduced as much as 64% for the city of Denver, and the lower reduction is 10% for the city of San Francisco.

In general, reduction of emission of pollutants from the use of CHP systems depend on the fraction of electric grid that is substituted by electricity from the PGU, and by the potential for pollution of the fuel mix for the electric grid when compared with the fuel consumed by the prime mover of the CHP system. Therefore, the combination of these two factors will define the advantages of CHP systems for reduction of emission of pollutants.

Table 5.5 Emission of Nitrogen Oxides (NO_x)

	PGU	Kg of NO_x		
City/Zone	Efficiency	Building	CHP	CHP-BPER
Denver Zone 1	0.25	737	518	544
	0.30		236	303
	0.35		182	182
Chicago Zone 2	0.25	690	493	510
	0.30		237	280
	0.35		184	184
Sterling Zone 3	0.25	489	359	370
	0.30		194	227
	0.35		155	155
San Francisco Zone 4	0.25	173	151	154
	0.30		120	134
	0.35		91	91
Tampa Zone 5	0.25	705	501	512
	0.30		416	430
	0.35		170	170

Table 5.6 Emission of Sulfur Dioxide (SO_2)

	PGU	Kg of SO_2		
City/Zone	Efficiency	Building	CHP	CHP-BPER
Denver Zone 1	0.25	447	291	310
	0.30		84	134
	0.35		50	50
Chicago Zone 2	0.25	2318	1514	1586
	0.30		444	635
	0.35		257	257
Sterling Zone 3	0.25	1398	909	958
	0.30		275	404
	0.35		153	153
San Francisco Zone 4	0.25	118	88	96
	0.30		45	66
	0.35		13	13
Tampa Zone 5	0.25	1099	714	735
	0.30		563	590
	0.35		109	109

Table 5.7 Emission of Carbon Dioxide (CO_2)

	PGU Efficiency	Kg of CO_2		
City/Zone		Building	CHP	CHP-BPER
Denver Zone 1	0.25	510612	383321	396563
	0.30		221181	257800
	0.35		184402	184402
Chicago Zone 2	0.25	421992	330244	336622
	0.30		213271	232086
	0.35		183600	183600
Sterling Zone 3	0.25	321685	261077	265216
	0.30		188290	201288
	0.35		164249	164249
San Francisco Zone 4	0.25	192890	171657	174389
	0.30		142216	154268
	0.35		113063	113063
Tampa Zone 5	0.25	409644	320641	324630
	0.30		280031	285904
	0.35		168575	168575

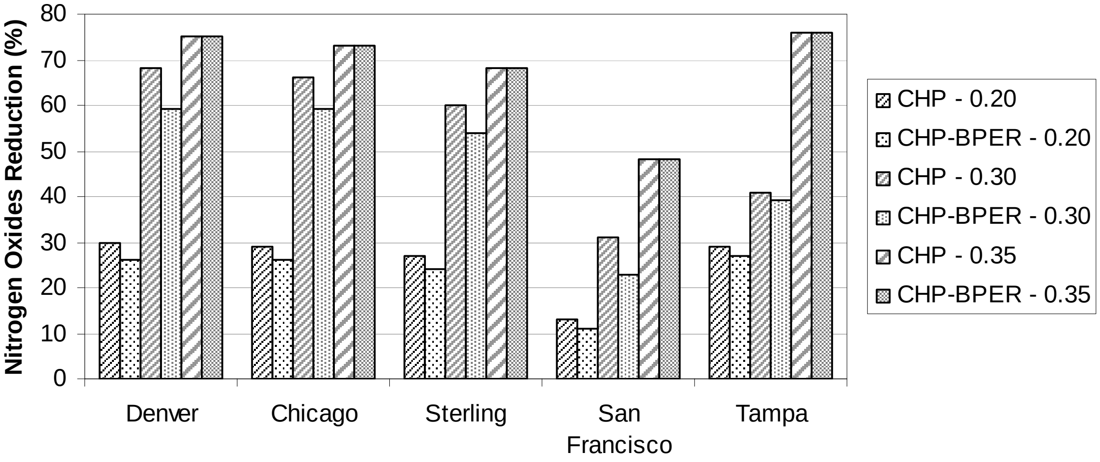


Figure 5.2 Nitrogen Oxides (NO_x) Reduction from the Use of CHP Systems

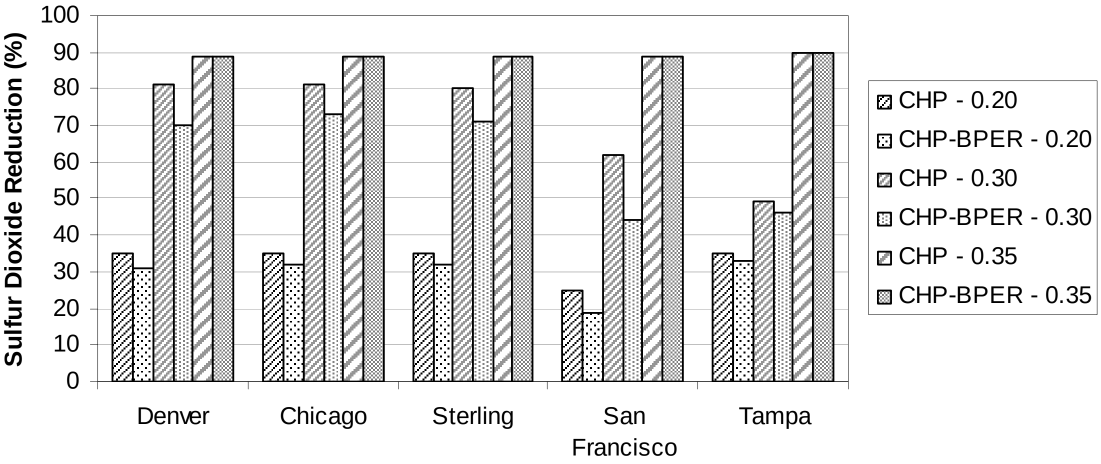


Figure 5.3 Sulfur Dioxide (SO_2) Reduction from the Use of CHP Systems

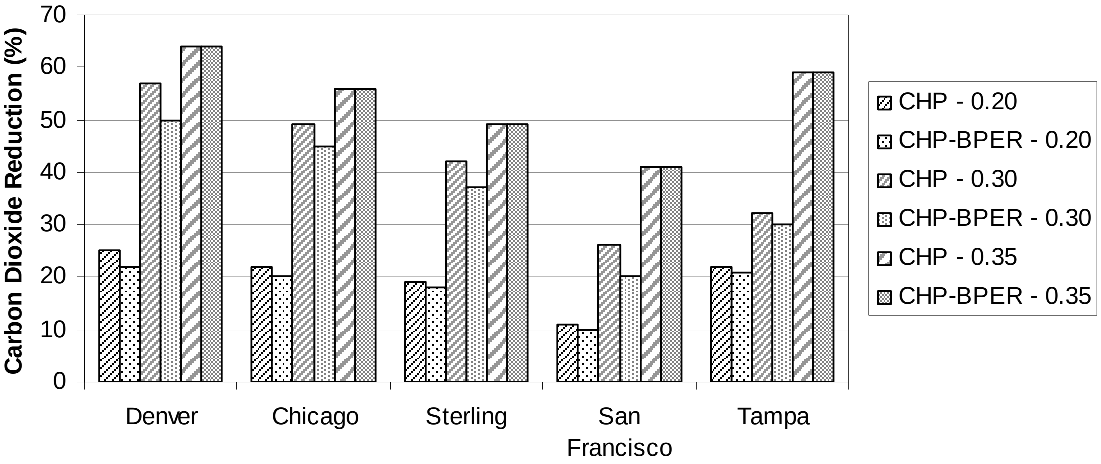


Figure 5.4 Carbon Dioxide (CO_2) Reduction from the Use of CHP Systems

5.5. CONCLUSION

When the actual Energy Star Rating of an office building is high enough, CHP systems have the potential to increase the rating above the minimum value of 75 required to go for an Energy Star certification. Since CHP systems increase Energy Star Rating, also have the potential to gain points for the LEED Rating. CHP systems will have more impact in a non-conventional evaluation based on energy ratings, if the building energy consumptions are close to the standards defined by Energy Star as benchmarks.

Because CHP system reduces energy consumption, and can use less pollutant fuels, it has great potential for reduction of emission of pollutants. Based on the results, seems that CHP systems allows enough reduction of emissions to consider economic benefits from Reduction Credits and Allowances.

CHAPTER VI

MODEL UNCERTAINTY

6.1 INTRODUCTION

The results presented in this study have been derived from the estimation of the CHP energy consumption using the model and simulation program described in Chapter II. For all model, verification and validation (V&V) are essential parts of model development. Verification precedes the validation to ensure that the model has been implemented properly, and does not contain errors or oversights. After results are obtained with the verified model, the validation follows by comparing the model results with experimental data. Because of the lack of experimental data, this chapter presents the first part of a V&V process which includes the determination of the uncertainties of the simulation results. Therefore, the purpose of the uncertainty analysis presented in this chapter is to use currently available information for the input variables in order to determine the degree of confidence of the model simulations (results).

The variables considered in the model were those that seem to be the most relevant for CHP system modeling and simulation. Uncertainty in the model inputs and how such errors propagate throughout the model can greatly affect the accuracy and understanding of the simulation results. Accordingly, it is expected that the uncertainty analysis presented in this chapter provides insight into the level of confidence in the simulations, and the identification of key sources of uncertainty for further research.

6.2 METHODOLOGY

6.2.1 Input Variables

The inputs for the simulation process that allows estimating the primary energy consumption include the building energy consumption and those related to CHP system components, such as efficiencies.

The building energy consumption input include building electric energy consumption, HVAC parasitic electricity, vapor compression electricity for cooling, fuel consumption for heating, and building fuel consumption for not heating use. These inputs can be obtained from real data through building commissioning or assumed actual building energy consumption from building simulation as done in this study. For a specific CHP system, different results can be obtained for different building energy consumption profiles. This implies that the uncertainty in the building energy consumption variables will define new sets of energy consumption profiles. Therefore, the uncertainty of these data is out of the scope of this study. However, because the uncertainty analysis is done for the five cases (cities energy consumption profiles) considered in the study, the results for the uncertainty analysis in some way account for the uncertainty in the energy consumption profiles.

The input variables for CHP system components considered for the uncertainty analysis are: heat recovery system efficiency (η_{rec}), vapor compression coefficient of performance (COP_{vc}), absorption chiller coefficient of performance (COP_{ch}), CHP boiler efficiency (η_b), heating system efficiency (η_h), increasing factors for parasitic electricity ($F_{p.c}, F_{p.h}$), and PGU efficiency (η_{pgu}).

6.2.2 Data Reduction Equations and Propagation of Uncertainty

The results of the simulation model correspond to the PEC for the cases when the CHP system runs without and with the BPER operational strategy, identified as CHP and CHP-BPER, respectively. Therefore, the data reduction equation for each case is defined as:

$$PEC_{CHP} = PEC_{CHP}\left(\eta_{rec}, COP_{vc}, COP_{ch}, \eta_b, \eta_h, F_{p.c}, F_{p.h}, \eta_{pgu}\right) \tag{6.1}$$

$$PEC_{CHP-BPER} = PEC_{CHP-BPER}\left(\eta_{rec}, COP_{vc}, COP_{ch}, \eta_b, \eta_h, F_{p.c}, F_{p.h}, \eta_{pgu}\right) \tag{6.2}$$

The simulation uncertainty can be determined using the uncertainty propagation equation [35]

$$U_r = \left[\left(\frac{\partial r}{\partial X_1}U_{X_1}\right)^2 + \left(\frac{\partial r}{\partial X_2}U_{X_2}\right)^2 + \cdots + \left(\frac{\partial r}{\partial X_J}U_{X_J}\right)^2\right]^{1/2} \tag{6.3}$$

However, because the complexity of the simulation program, the derivatives were determined numerically using a forward-differencing finite-difference approach [35] which is presented in the equation bellow

$$\left.\frac{\partial r}{\partial X_1}\right|_{X_2,\ldots,X_j \text{ constant}} \approx \frac{\Delta r}{\Delta X_1} \approx \frac{r_{X_1+\Delta X_1, X_2,\ldots,X_j} - r_{X_1, X_2,\ldots,X_j}}{\Delta X_1} \tag{6.4}$$

with similar expressions for the derivatives with respect to X_2, X_3,…,X_j. Then, the uncertainty in the result is computed as

$$U_r^2 \approx \left(\frac{\Delta r}{\Delta X_1} U_{x_1}\right)^2 + \left(\frac{\Delta r}{\Delta X_2} U_{x_2}\right)^2 + \cdots + \left(\frac{\Delta r}{\Delta X_j} U_{x_j}\right)^2 \qquad (6.5)$$

6.2.3 Nondimensionalized Form of Uncertainty in the Results

In order to understand how the uncertainty of the variables impact on the uncertainty in the results, the Uncertainty Magnification Factors (UMFs) and Uncertainty Percentage Contributions (UPCs) are considered in this analysis. The UMF and UPC can be determined using Equations (6.6) and (6.7), respectively.

$$UMF_i = \frac{X_i}{r} \frac{\partial r}{\partial X_i} \qquad (6.6)$$

$$UPC_i = \frac{(\partial r / \partial X_i)^2 (U_{X_i})^2}{U_r^2} \times 100 \qquad (6.7)$$

As stated by Coleman and Steele [35], the “UMF for a given X_i indicates the influence of the uncertainty in that variable on the uncertainty in the result,” while, the “UPC for a given X_i gives the percentage contribution of the uncertainty in the variable to the squared uncertainty in the result.”

6.3 UNCERTAINTY ANALYSIS

6.3.1 Uncertainty of the Input Variables

Table 6.1 presents the uncertainties for the input variables used in the simulation calculations to estimate the uncertainty in the results. The results correspond to the uncertainty in the PEC_{CHP} and $PEC_{CHP\text{-}BPER}$, which are presented in Section 6.4.

As can be seen in Table 6.1, most of the input variables are system component efficiencies. These efficiencies are usually declared by the manufacturer or can be calculated based on other technical information supplied by the manufacturer in the equipment specifications. Usually no information is provided by the manufacturer about the uncertainties for the given efficiencies, output (power, cooling capacity, etc), or inputs (fuel consumption, heat rate, etc). However, because the manufacturers must follow the industry standards, it is assumed that the declared values have a reasonable uncertainty. Therefore, the uncertainties associated with the input variables presented in Table 6.1 were estimated based on manufacturer's technical specifications, literature review, and engineering judgment. The uncertainty of the absorption chiller coefficient of performance has a slightly overestimated uncertainty because of limited information. This uncertainty was overestimate using a criterion based on the reduction of the COP due to partial load operation. A particular situation arises for the increasing factors for parasitic electricity ($F_{p.c}, F_{p.h}$). These factors were introduced into the model to account for the increment of the parasitic electricity as consequence of new equipment (pumps, fans) required by the CHP system. However, the new equipment, its capacity, and energy consumption, depend on the specific capacity, characteristics, and layout of the CHP system. Thus, an uncertainty for these factors is difficult to estimate based on the scope of this study, and any reasonable value could be as correct as over or underestimated. Therefore, a 15% uncertainty for $F_{p.c}, F_{p.h}$ was considered in this study.

Table 6.1 Uncertainty for the Input Variables

Variable	%
Heat recovery system efficiency	6
Vapor compression coefficient of performance	5
Absorption chiller coefficient of performance	8
CHP boiler efficiency	5
Heating system efficiency	6
Increasing factor for cooling parasitic electricity	15
Increasing factor for heating parasitic electricity	15
PGU efficiency	6

6.3.2 UMFs and UPCs

By using the uncertainties for the input variables presented in Table 6.1, the UMFs and UPCs were computed. Figures 6.1 to 6.5 illustrate the UMFs and UPCs for the cities of Denver, Chicago, Sterling, San Francisco, and Tampa, respectively. Each figure presents the UMFs and UPCs for the PGU efficiencies considered in this study, (a) 0.25, (b) 0.30, and (c) 0.35.

As expected from previous results, the influence of input variables uncertainties on the uncertainty in the result depends on the building energy consumption profiles. However, the uncertainty of the PGU efficiency shows its dominance for most of the cases. Similarly to previous behavior of CHP systems for energy consumption, as the PGU efficiency becomes similar or higher than the utility power plant efficiency, the behavior of the input variables uncertainties tends to be similar independently of the building energy consumption profile. For this situation, the dominance of the uncertainty of the PGU efficiency is higher than for lower PGU efficiencies.

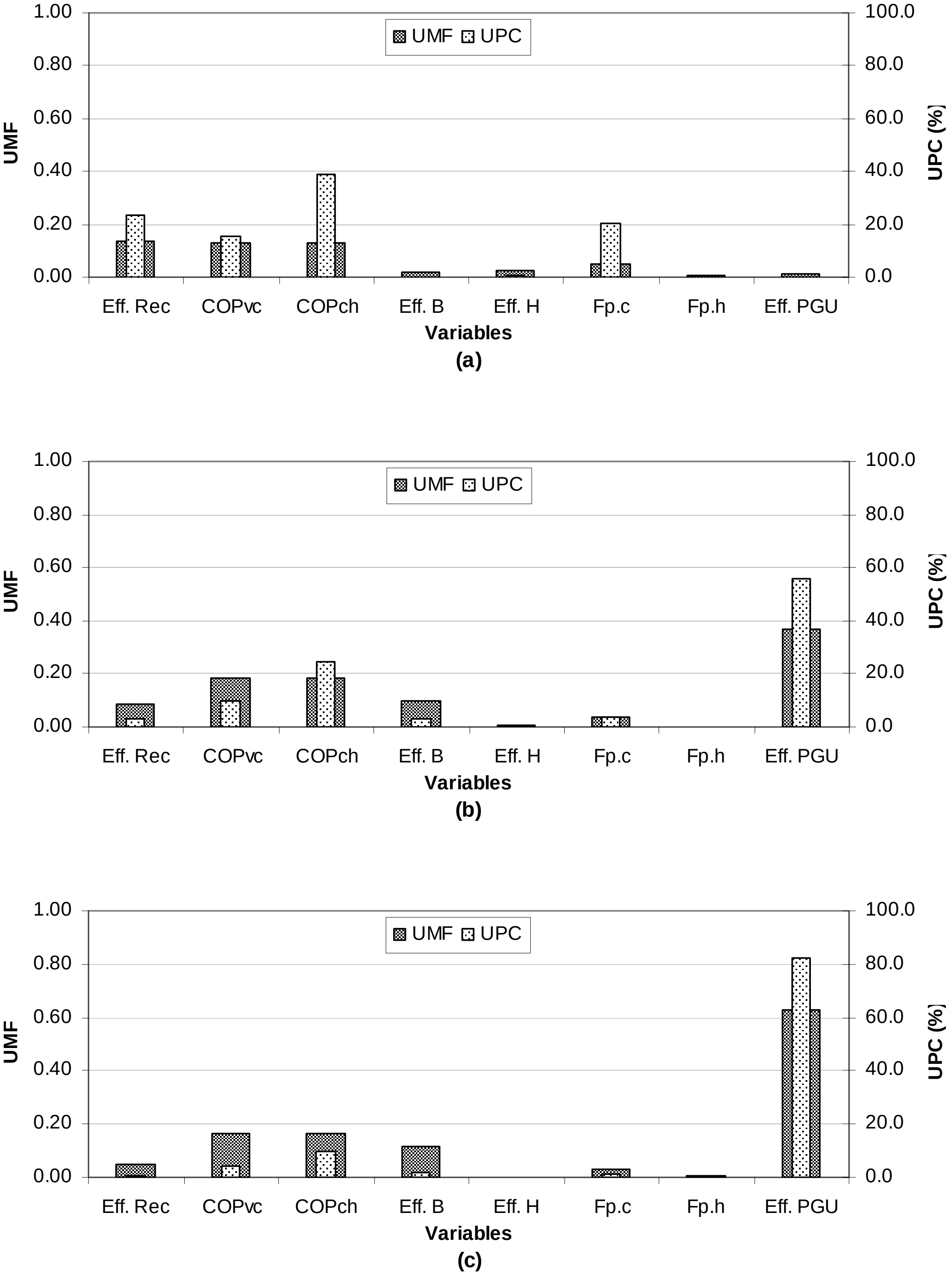


Figure 6.1 UMFs and UPCs for Denver, η_{pgu} (a) 0.25, (b) 0.30, and (c) 0.35

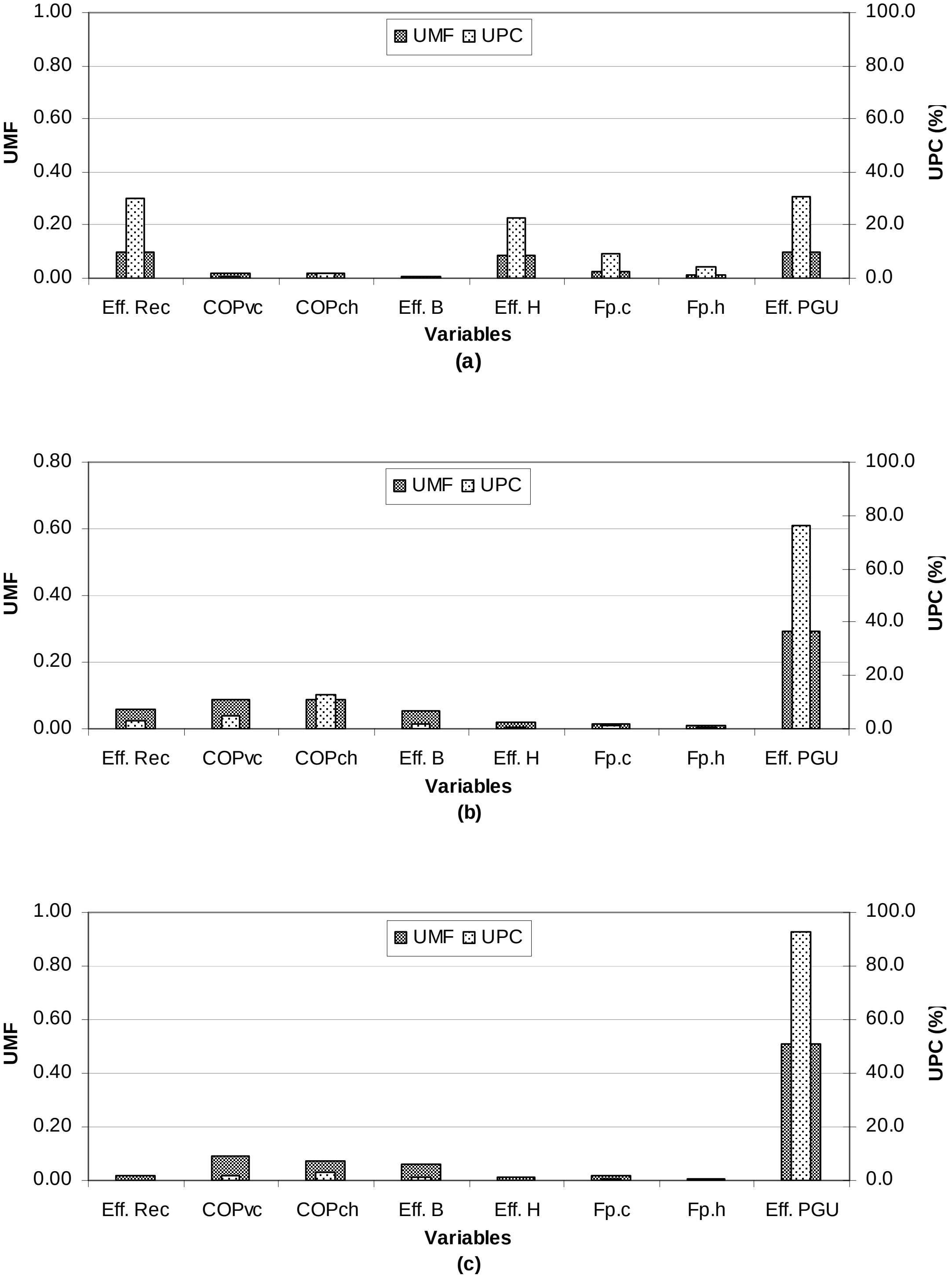


Figure 6.2 UMFs and UPCs for Chicago, η_{pgu} (a) 0.25, (b) 0.30, and (c) 0.35

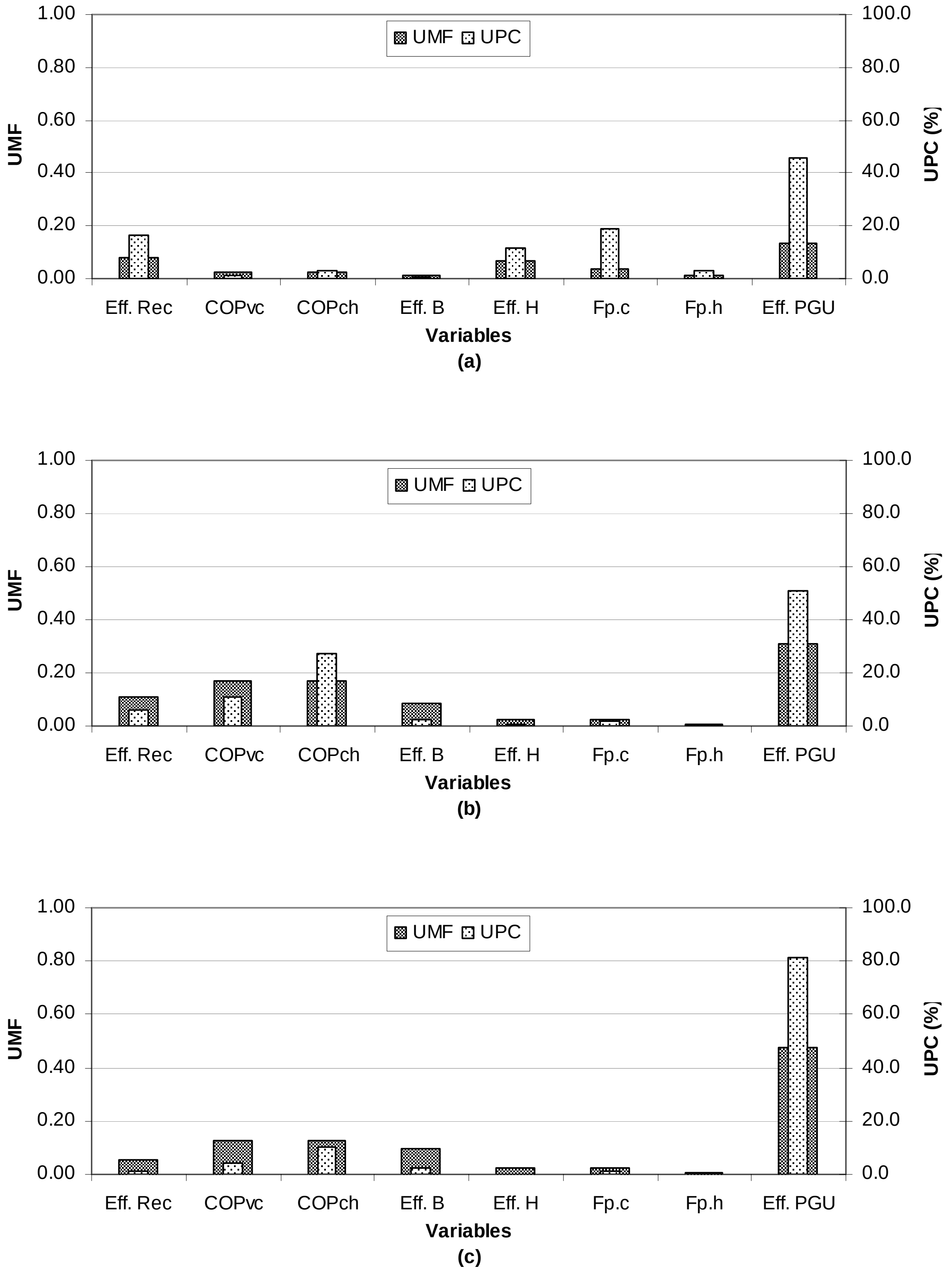
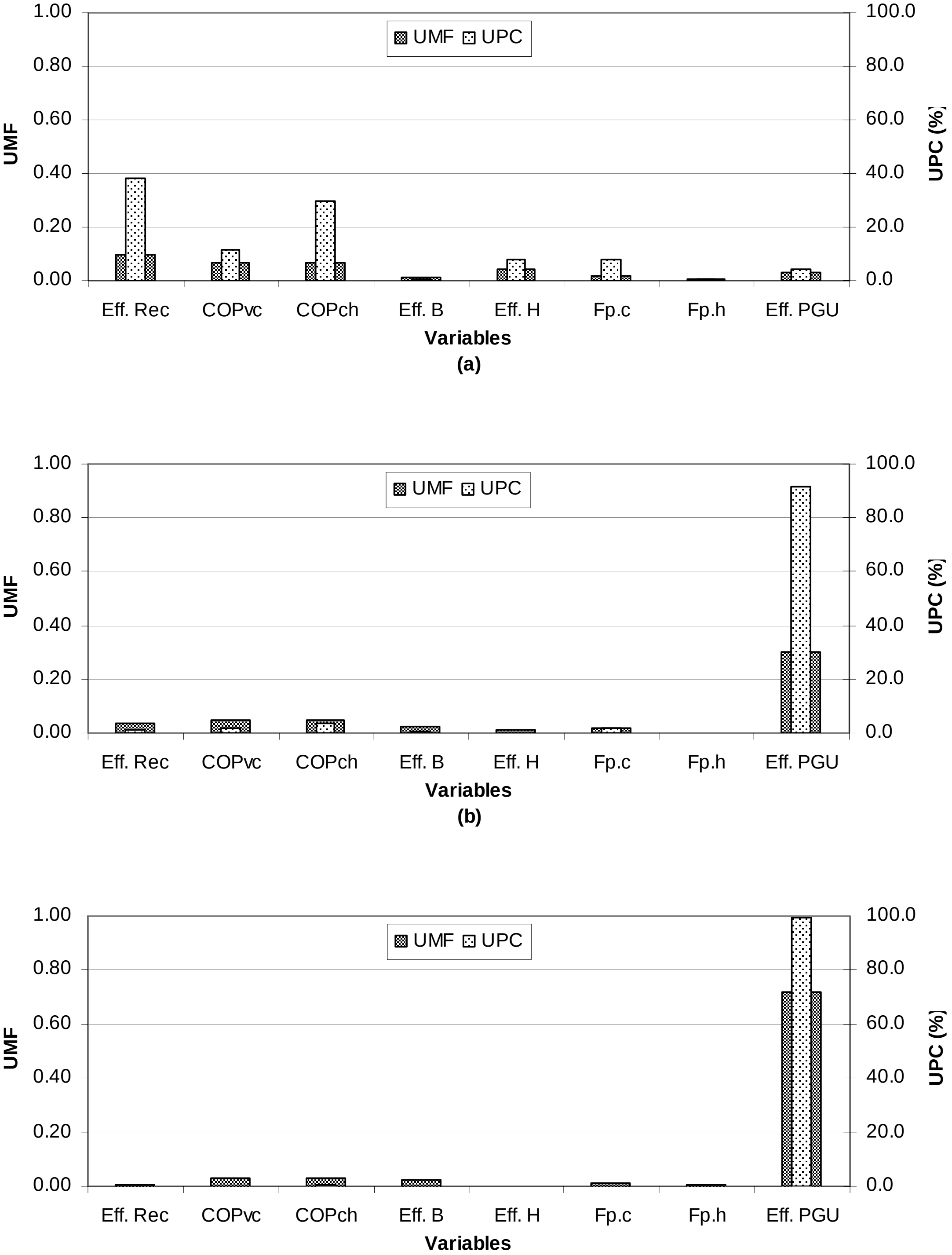


Figure 6.3 UMFs and UPCs for Sterling, η_{pgu} (a) 0.25, (b) 0.30, and (c) 0.35



(a)

(b)

(c)

Figure 6.4 UMFs and UPCs for San Francisco, η_{pgu} (a) 0.25, (b) 0.30, and (c) 0.35

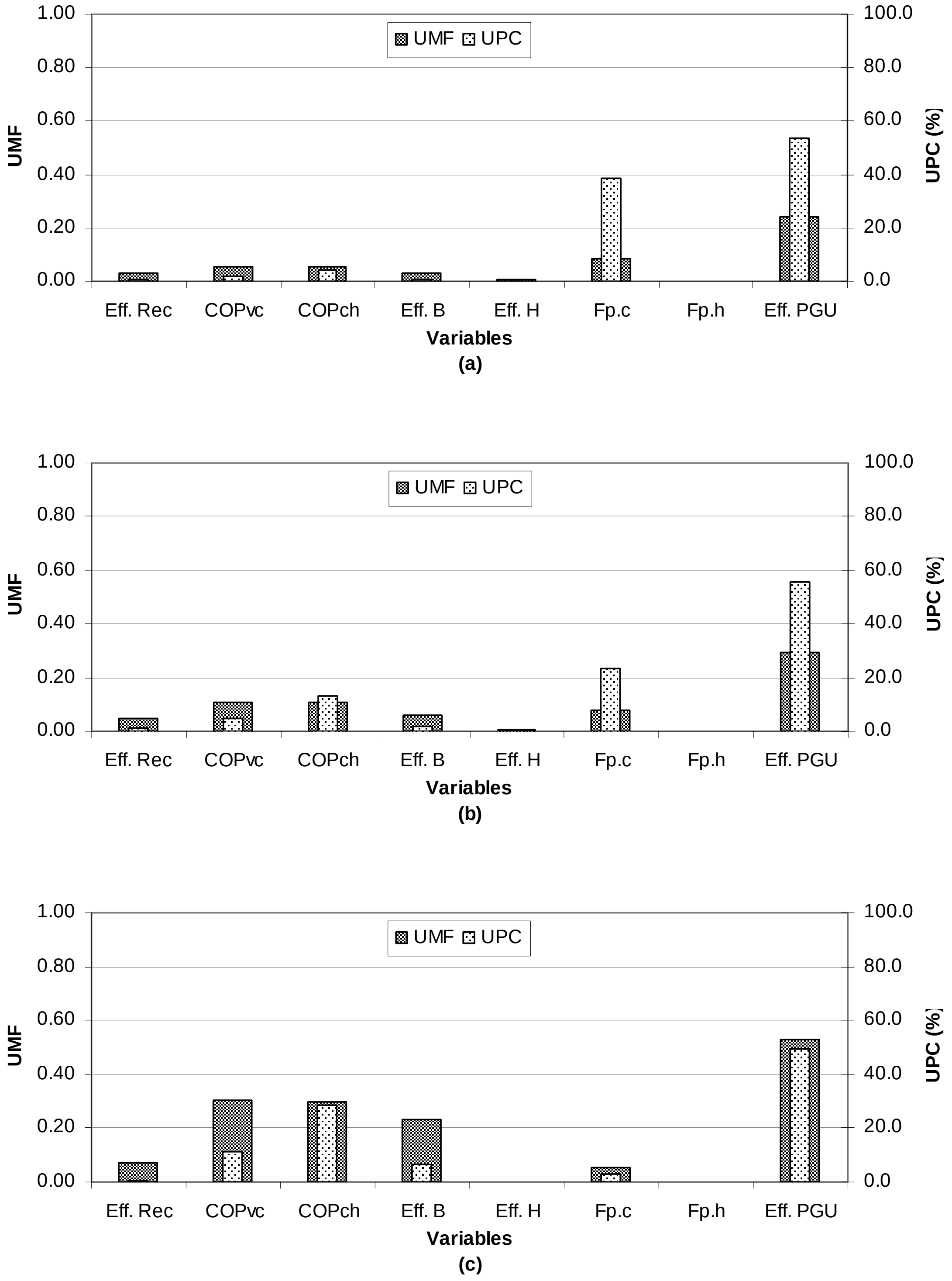


Figure 6.5 UMFs and UPCs for Tampa, η_{pgu} (a) 0.25, (b) 0.30, and (c) 0.35

6.4 UNCERTAINTY IN THE RESULTS

Table 6.2 presents the uncertainty for the primary energy consumption for the cases when the CHP system runs without and with the BPER operational strategy. The uncertainty for $PEC_{CHP\text{-}BPER}$ is slightly lower than for PEC_{CHP}, which is expected from the better performance obtained when the BPER operational strategy is applied. On the other hand, similar to the energy consumption, for high PGU efficiency the uncertainty for PEC is the same for the cases when CHP systems run without and with the BPER operational strategy. This is due to the CHP system behaving in the same way for both cases (CHP and CHP-BPER) when the PGU efficiency becomes similar or higher than the utility power plant efficiency.

The building energy consumption profile affects the CHP system energy consumption profile, and consequently affects the uncertainty in the results. However, the maximum difference for the uncertainty in the PEC found for all cases are 0.69%, 1.07%, and 1.33%, for the PGU efficiencies of 0.25, 0.30, and 0.35, respectively. These low variations verify the stability of the simulation model for different energy consumption profiles. As predicted by the UMF and the UPC, the efficiency of the power generation unit has a significative weight on the results. The higher the PGU efficiency, the higher the uncertainty in the results.

Because of the difficulty to estimate the uncertainty for the increasing factors for parasitic electricity ($F_{p.c}, F_{p.h}$), additional analysis was done for these input variables. The uncertainty in the PEC, for the case when the CHP system is operated using the BPER operational strategy ($PEC_{CHP\text{-}BPER}$), was also estimated for uncertainties of 5% and

10% and compared with the initial assumed value of 15%. The comparison results are presented in Figure 6.6 for all cities in this study. This figure proves that the uncertainty of the increasing factors for parasitic electricity does not compromise the uncertainty in the results since the values are similar for the analyzed range.

Table 6.2 Uncertainty in the Primary Energy Consumption

	PGU	Uncertainty (%)	
City/Zone	Efficiency	PEC_{CHP}	$PEC_{CHP\text{-}BPER}$
Denver Zone 1	0.25	1.69	1.66
	0.30	3.09	2.95
	0.35	4.15	4.15
Chicago Zone 2	0.25	1.17	1.09
	0.30	2.29	2.03
	0.35	3.17	3.17
Sterling Zone 3	0.25	1.33	1.19
	0.30	2.92	2.58
	0.35	3.16	3.16
San Francisco Zone 4	0.25	1.12	0.97
	0.30	2.88	1.88
	0.35	4.32	4.32
Tampa Zone 5	0.25	2.09	0.97
	0.30	2.47	2.35
	0.35	4.49	4.49

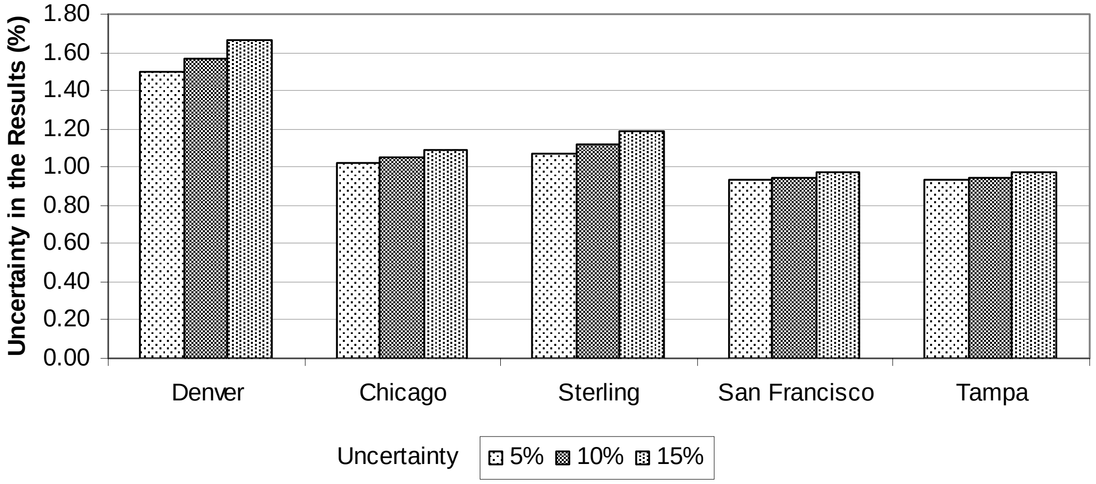


Figure 6.6 Effect of the $F_{p.c}$ and $F_{p.h}$ Uncertainties on Uncertainty in the Results

6.5 CONCLUSION

This chapter presented an uncertainty analysis of the simulation program implemented for the model developed in this dissertation to estimate the building-CHP system energy consumption. The uncertainty of the simulation results for the PEC_{CHP} has a range of 1.12% to 4.49%, while the uncertainty for the $\text{PEC}_{\text{CHP-BPER}}$ has a range of 0.97% to 4.49%. The higher uncertainties are found for higher PGU efficiencies. The uncertainty in the results from the simulation program varies with the building energy consumption profiles. This uncertainty analysis lays the foundation upon which a quantitative V&V effort can begin to take shape.

CHAPTER VII

CONCLUSIONS AND FUTURE WORK

7.1 CONCLUSIONS

- A model to estimate the energy consumption of CHP systems was developed. The model accounts for the most significant variables governing the energy consumption from the use of CHP systems in buildings. The model also takes in consideration the logic of the energy flow and energy consumption through the components of the CHP system. The implementation of the model in the simulation program allows varying the capacity of the power generation unit and the capacity of the absorption chiller in order to find the optimum sizes for the best energy performance of the overall system.
- A methodology to evaluate CHP systems energy performance based on primary energy was developed by using a novel parameter introduced in this investigation called Building Primary Energy Ratio (BPER). This parameter allows comparing the primary energy consumption for a building with and without a CHP system. In the simulation program, this parameter allows to simulate the energy performance under a primary energy operational strategy in order to obtain the lowest primary energy consumption for the specified inputs. The primary energy operational strategy introduced in this investigation guarantee primary energy

savings which not always is achieved using the common cost-oriented operational strategy.

- The use of the primary energy operational strategy can guarantee energy savings from the use of CHP systems, but the economic feasibility is subject to energy prices. When energy prices make economically unfeasible a well designed CHP system, other benefits from this technology must be considered. Other benefits could be identified from non-economic evaluations which may include aspects such as power reliability, power quality, environmental quality, energy-efficient buildings (energy ratings), fuel source flexibility, brand and marketing benefits, protection from electric rate hikes, and benefits from promoting energy management practices. Some benefits from a non-conventional evaluation could be quantified and transferred into the economic evaluation, while others would give intangible potential to the technology.
- A methodology to evaluate CHP systems benefits on the Energy Star and the Leadership in Energy and Environmental Design (LEED) Ratings was developed. These methodologies can be used as part of a non-conventional evaluation of CHP systems in order to overcome economic weakness of CHP technology as consequence of the fluctuating energy prices. The key in using these methodologies is the web based tool Target Finder from the Energy Star program of the U.S.A. Department of Energy, which provides two important characteristics to the proposed methodology: readily access and relevance.
- A methodology to estimate the emissions reduction of pollutants from the use of CHP systems was also developed. Emissions reduction of pollutants is perhaps

one of the most important factors of a non-conventional evaluation of CHP systems. The methodology uses the web tool Power Profiler of the U.S. Environmental Protection Agency (EPA) which provides two important characteristics to the proposed methodology: readily access and relevance. This methodology not only allows showing the environmental benefits of CHP systems, but also can be used to estimate the carbon credits that could be translated into economic benefits.

- The first step for the verification and validation process was accomplished through the model uncertainty analysis.
- Additional contributions to the initial objectives proposed in this research are:
    - A methodology to convert annual energy consumption into monthly energy consumption was developed. To achieve this, the concept of Heating, and Cooling Degree-Days were used to estimate the heating (space and water) and cooling energy consumptions from annual energy consumptions.
    - A comparison between the energy consumption based on hourly and monthly energy consumptions show that although CHP systems analysis based on monthly data are important as first step for CHP systems feasibility. Therefore, the results obtained from the monthly data must be carefully used because errors of more than 20% could be achieved.

7.2 FUTURE WORK

- Results from this research have proved that CHP systems performance strongly depends on the building energy consumption (electricity and fuel) profiles.

Therefore, since the Building Primary Energy Ratio allows obtaining the best energy performance from specific inputs, the impact of energy management strategies to reduce energy use can be assessed as a complement of a CHP system. This will allow obtaining the best cost-benefit relation between CHP systems and energy conservation retrofits.

- The CHP system simulation program implemented based on the developed model can be used to size the power generation unit and absorption chiller that gives the best energy performance. However, further research should be carried out to evaluate the benefits of the use of several power generation units and/or several absorption chillers.
- Since the operational strategy defines the ultimate goal of a CHP system, the development of a CHP system simulation program that allows defining the operational strategy would be very useful. This tool would allow designers and engineers to obtain the best design based on the owners and/or facility managers' goals.
- Since CHP systems reduces the primary energy consumption using less pollutant fuels, developing a methodology to determine how to translate emission reduction into economic benefits would be relevant to strength the economic feasibility of CHP systems.

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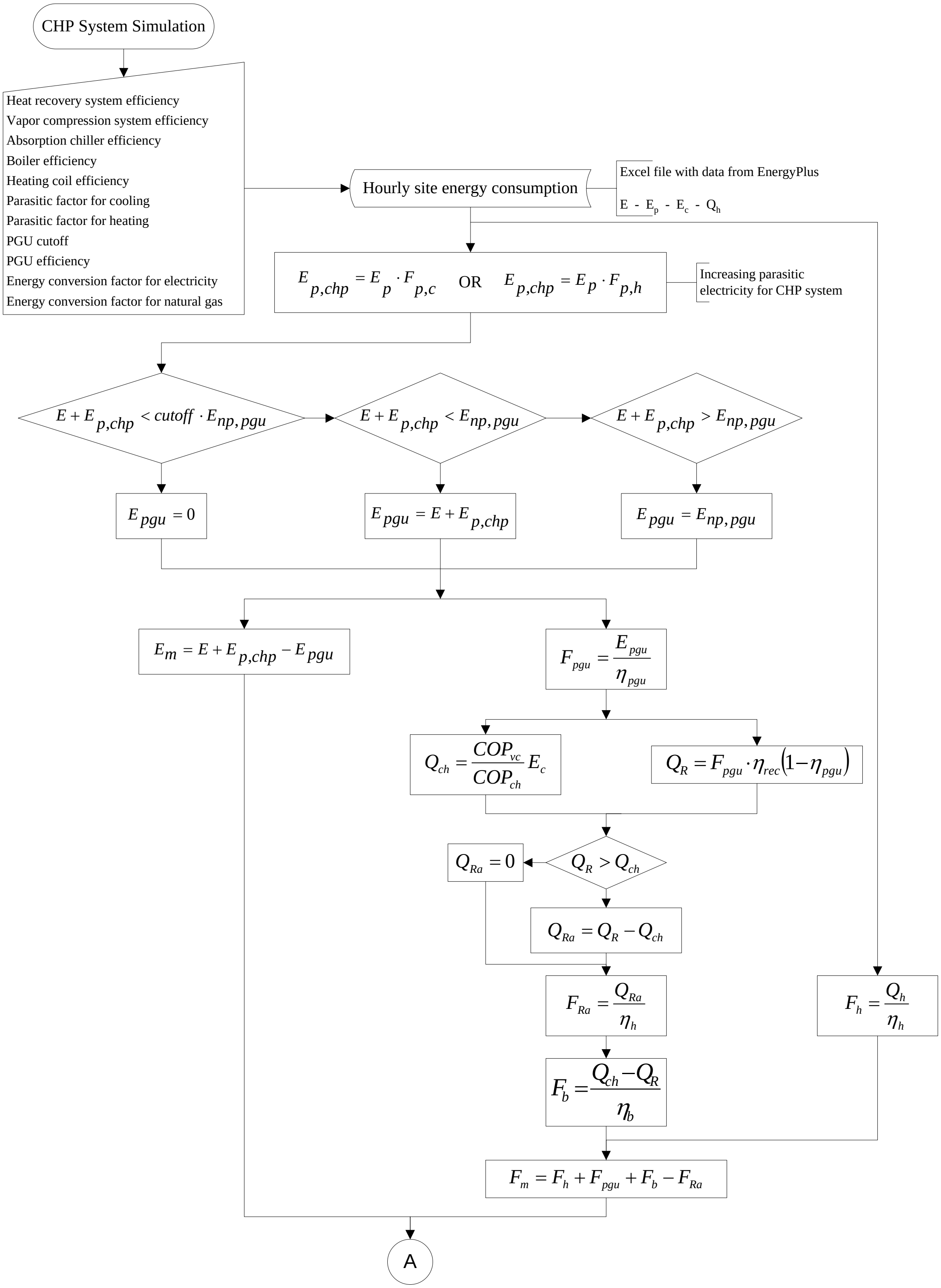
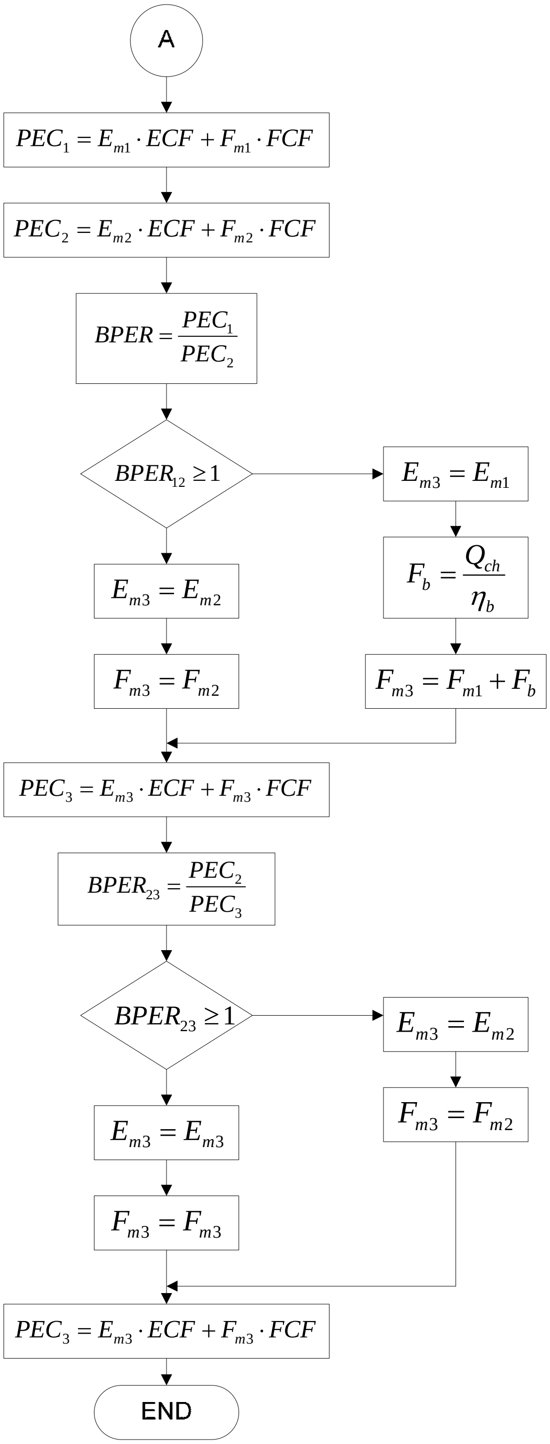
APPENDIX A

FLOWCHART FOR THE CHP SYSTEM SIMULATION PROGRAM


CHP System Simulation
Heat recovery system efficiency
Vapor compression system efficiency
Absorption chiller efficiency
Boiler efficiency
Heating coil efficiency
Parasitic factor for cooling
Parasitic factor for heating
PGU cutoff
PGU efficiency
Energy conversion factor for electricity
Energy conversion factor for natural gas
Hourly site energy consumption
Excel file with data from EnergyPlus
E - E_p - E_c - Q_h
$E_{p,chp} = E_p \cdot F_{p,c}$ OR $E_{p,chp} = E_p \cdot F_{p,h}$
Increasing parasitic electricity for CHP system
$E + E_{p,chp} < cutoff \cdot E_{np,pgu}$
$E + E_{p,chp} < E_{np,pgu}$
$E + E_{p,chp} > E_{np,pgu}$
$E_{pgu} = 0$
$E_{pgu} = E + E_{p,chp}$
$E_{pgu} = E_{np,pgu}$
$E_m = E + E_{p,chp} - E_{pgu}$
$F_{pgu} = \frac{E_{pgu}}{\eta_{pgu}}$
$Q_{ch} = \frac{COP_{vc}}{COP_{ch}} E_c$
$Q_R = F_{pgu} \cdot \eta_{rec} (1 - \eta_{pgu})$
$Q_{Ra} = 0$
$Q_R > Q_{ch}$
$Q_{Ra} = Q_R - Q_{ch}$
$F_{Ra} = \frac{Q_{Ra}}{\eta_h}$
$F_h = \frac{Q_h}{\eta_h}$
$F_b = \frac{Q_{ch} - Q_R}{\eta_b}$
$F_m = F_h + F_{pgu} + F_b - F_{Ra}$
A


A
$PEC_1 = E_{m1} \cdot ECF + F_{m1} \cdot FCF$
$PEC_2 = E_{m2} \cdot ECF + F_{m2} \cdot FCF$
$BPER = \frac{PEC_1}{PEC_2}$
$BPER_{12} \geq 1$
$E_{m3} = E_{m1}$
$F_b = \frac{Q_{ch}}{\eta_b}$
$F_{m3} = F_{m1} + F_b$
$E_{m3} = E_{m2}$
$F_{m3} = F_{m2}$
$PEC_3 = E_{m3} \cdot ECF + F_{m3} \cdot FCF$
$BPER_{23} = \frac{PEC_2}{PEC_3}$
$BPER_{23} \geq 1$
$E_{m3} = E_{m2}$
$F_{m3} = F_{m2}$
$E_{m3} = E_{m3}$
$F_{m3} = F_{m3}$
$PEC_3 = E_{m3} \cdot ECF + F_{m3} \cdot FCF$
END

APPENDIX B

SITE ENERGY CONSUMPTION BY TYPE OF SOURCE

		Building			CHP			CHP-BPER		
		Electricity	Natural Gas		Electricity	Natural Gas		Electricity	Natural Gas	
City (Zip Code)	PGU Efficiency	kWh	kWh	MBTU	kWh	kWh	MBTU	kWh	kWh	MBTU
Denver (80210)	0.25	205061	306705	1046	132974	487155	1662	141707	453075	1546
	0.30	205061	306705	1046	38191	753259	2570	60843	677972	2313
	0.35	205061	306705	1046	22591	741338	2529	22591	741338	2529
Chicago (60610)	0.25	208373	378750	1292	136059	549355	1874	142529	523997	1788
	0.30	208373	378750	1292	39864	804307	2744	57063	747154	2549
	0.35	208373	378750	1292	23030	798147	2723	23030	798147	2723
Sterling (20165)	0.25	217396	276821	945	141152	467988	1597	148783	438203	1495
	0.30	217396	276821	945	42542	746283	2546	62609	679664	2319
	0.35	217396	276821	945	23570	744392	2540	23570	744392	2540
San Francisco (94110)	0.25	180490	110212	376	134601	235738	804	146061	190191	649
	0.30	180490	110212	376	66593	433006	1477	100494	320143	1092
	0.35	180490	110212	376	17752	530414	1810	17752	530414	1810
Tampa (33610)	0.25	280066	23410	80	182025	315584	1077	187423	294448	1005
	0.30	280066	23410	80	143205	401629	1370	150163	378428	1291
	0.35	280066	23410	80	27474	711191	2427	27474	711191	2427

APPENDIX C

REGION FUEL MIX COMPARISON

The figure shows the fuel mix comparison for the grid regions corresponding to each of the cities considered in this study. This figure was developed based on the information provided by Power Profile. The fuel mix will define the amount of pollutants when electricity is consumed, and consequently will define the impact of CHP systems on the reduction of emission of pollutants. For the cities of Denver, Chicago, and Sterling, more than 50% of the electric power comes from coal which is highly pollutant. While for the cities of San Francisco and Tampa, more than 70% of the electric power comes from sources other than fossil fuels. Then, for the same energy consumption among the evaluated cities, more pollutants will be generated in the cities of Denver, Chicago, and Sterling, than in the cities of San Francisco and Tampa.