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Analysis and optimization of CHP, CCHP, CHP-ORC, and CCHP-ORC systems

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ANALYSIS AND OPTIMIZATION OF CHP, CCHP, CHP-ORC, AND CCHP-ORC

SYSTEMS

By

Anna Kathrine Hueffed

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ANALYSIS AND OPTIMIZATION OF CHP, CCHP, CHP-ORC, AND CCHP-ORC

SYSTEMS

By

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Increased demand for energy, rising energy costs, and heightened environmental concerns are driving forces that continually press for the improvement and development of new technologies to promote energy savings and emissions reduction. Combined heating and power (CHP), combined cooling, heating, and power (CCHP), and organic Rankine cycles (ORC) are a few of the technologies that promise to reduce primary energy consumption (PEC), cost, and emissions. CHP systems generate electricity at or near the place of consumption using a prime mover, e.g. a combustion engine or a turbine, and utilize the accompanying exhaust heat that would otherwise be wasted to satisfy the building's thermal demand. In the case of CCHP systems, exhaust heat also goes to satisfy a cooling load. An organic Rankine cycle (ORC) combined with a CHP or CCHP system can generate electricity from any surplus low-grade heat, thereby reducing the total primary energy, cost, and emissions.

This research first presents a review of the economical, energetic, and environmental benefits of CHP and CHP-ORC systems for a small office in various climates. Operating the systems 24 hours a day is compared to operating the system during typical office hours and benefits of the CHP system in terms of the EnergyStar and LEED programs are presented. Another objective of this dissertation is to study the critical role of the prime mover on the performance of CHP, CCHP, CHP-ORC, and CCHP-ORC systems under different pricing structures. Three different size natural gas engines are simulated for a small office under different operational strategies such as: follow the facility's electric demand, follow the facility's thermal demand, and follow a constant load. Simple optimizations were carried out to improve the system's performance. Using real prices for electricity and fuel to compute operational costs was compared to using the building's average prices without a CCHP system. Finally, a CCHP system using a load-share turbine for a large office building was examined while considering the source of carbon dioxide emissions, carbon offsetting through purchasing carbon credits, and available capital costs.

Key words: CHP, CCHP, ORC, primary energy, carbon dioxide emissions, operational strategies, LEED, EnergyStar, carbon credits

DEDICATION

To my dad.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Variables

a, a', a'', a'''	Coefficients for turbine efficiency curve
A	Coefficient for boiler efficiency curve
b, b', b'', b'''	Coefficients for turbine efficiency curve
B	Coefficient for boiler efficiency curve
$BlockCharges$	Block charges in the monthly utility bill
c, c', c'', c'''	Coefficients for turbine efficiency curve
$CapitalCost$	Capital cost
C	Coefficient for boiler efficiency curve
CC	Carbon credit value
CDE	Annual carbon dioxide emissions
$CDE_{electricity}$	Carbon dioxide emissions resulting from the production of delivered electricity
$CDE_{fuel-boiler}$	Carbon dioxide emissions resulting from fuel combustion in the onsite boiler
$CDE_{fuel-pgu}$	Carbon dioxide emissions resulting from fuel combustion in the onsite PGU
$CDE_{fuel-pre}$	Pre-combustion carbon dioxide emissions resulting from fuel extraction, processing, and delivery
$CF_{CDE,e}$	Carbon dioxide emissions conversion factor for electricity
$CF_{CDE,ng}$	Carbon dioxide emissions conversion factor for natural gas

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$CF_{CDE,ng\text{-}boiler}$	Carbon dioxide emission conversion factor for on-site natural gas combustion in a boiler
$CF_{CDE,ng\text{-}pgu}$	Carbon dioxide emission conversion factor for on-site natural gas combustion in PGU
$CF_{CDE,ng\text{-}pre}$	Carbon dioxide emission conversion factor for natural gas precombustion
$CF_{PEC,e}$	Primary energy consumption conversion factor for electricity
$CF_{PEC,ng}$	Primary energy consumption conversion factor for natural gas
COP	Coefficient of performance
$Cost$	Annual operational cost – does not include any carbon purchases
$Cost_e$	Monthly cost of grid electricity
$Cost_{hour}$	Marginal cost to operate CHP facility for a given hour
$Cost_{ng}$	Monthly cost of natural gas
$Cost_{total}$	Annual cost to operate facility (includes purchasing carbon credits to offset emissions)
d	Coefficient for turbine efficiency curve
e	Coefficients for turbine efficiency curve
E	Electricity
$E_{CHP\text{-}ORC}$	Electric output of CHP-ORC system
$E_{equipment}$	Electricity needed to run office equipment
E_{export}	Electricity exported to the grid
E_{fans}	Electricity to run HVAC fans
E_{grid}	Electricity imported from the grid
E_{lights}	Electricity required to operate the lights

E_{min}	Minimum electric output of PGU
E_{ORC}	Electric output of ORC
E_{pgu}	Electricity generated by the PGU
E_{pgu}°	Electric output of PGU that results in $E_{CHP\text{-}ORC} = E_{req}$ or $E_{CCHP\text{-}ORC} = E_{req}$
$E_{Q_{req}}$	PGU electric output that results in the recovery of Q_{req}
E_{ref}	Electricity consumed by the reference building
E_{req}	Total electricity required by office building
E_{vcs}	Electricity required by vapor compression system
F_{boiler}	Fuel energy input to boiler
$EnergyCharges$	Base cost for monthly utility bill based on energy consumption
F_{pgu}	Fuel energy input to PGU
F_{ref}	Fuel energy consumption of the reference case
h	Enthalpy
L	Prime mover rated load
LR	Load ratio
m	Mass flow rate over an hour for the organic working fluid in the ORC
mr	Marginal rate
p	Average price
$Payback$	Simple payback period
PEC	Annual primary energy consumption
q_e	Specific heat transer in the evaporator
Q_{boiler}	Heat produced by the boiler
Q_c	Cooling load of office (only applies for heat-driven cooling)

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Q_{ch}	Heat needed to operate absorption chiller (= Q_c/η_{ch})
Q_e	Heat absorbed by the ORC working fluid in the evaporator
Q_h	Heating load of office
Q_{hc}	Heat needed to run heating coil (= Q_h/η_{hc})
Q_{hw}	Hot water load of office
Q_{hws}	Heat required to run hot water system (= Q_{wh}/η_{hws})
Q_{rec}	Heat recovered from the PGU exhaust
Q_{req}	Total heat required from recovered PGU exhaust and/or the boiler
r	Price
$Savings_{CHP}$	Operational savings from using a CHP system over the reference case
$Subtotal$	Monthly utiltiy bill subtotal (before taxes)
t	Tax rate
w	Specific work
x	Air and fuel input for boiler efficiency curve (as a percent)

Abbreviations

CCHP	Combined cooling, heating, and power
CCHP-ORC	Combined CCHP and ORC
CCX	Chicago Climate Exchange
CDE	Carbon dioxide emissions
CHP	Combined heating and power
CHP-ORC	Combined CHP and ORC
DOE	Department of Energy
FEL	Follow(ing) the electric load

FELc	Follow(ing) the electric load with cutoff
FTL	Follow(ing) the thermal load
FTLc	Follow(ing) the thermal load with cutoff
FSS	Follow(ing) a seasonal strategy
HVAC	Heating, ventilating, and air conditioning
LEED	Leadership in Energy and Environmental Design
LEED-EB	LEED for existing buildings
NREL	National Renewable Energy Lab
On	Fraction of the year that the optimized CCHP system is operating
Opt	Optimization
ORC	Organic Rankine cycle
PEC	Primary energy consumption
PGU	Power generation unit (prime mover and generator)
REF	Reference building (no CHP system)

Greek

α	Coefficient for engine fuel consumption curve
β	Coefficient for engine fuel consumption curve
Δ_{cost}	Difference in capital costs of a CHP system and reference building
ε	Effectiveness of ORC evaporator
γ	Ratio of the reduced electricity consumption to the increase in natural gas consumption
η	Efficiency
η_B	Overall efficiency of CCHP building
η_{CCHP}	Efficiency of CCHP system

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φ_{CDE}	Ratio of electricity CDE conversion factor to the natural gas CDE conversion factor
φ_{cost}	Ratio of the average electricity price to the average natural gas price
φ_{cost}	Ratio of electricity PEC conversion factor to the natural gas PEC conversion factor

Subscripts

ch	Absorption chiller
e	Electricity
gen	ORC generator
hc	Heating coil
hws	Hot water system
ng	Natural gas
p	ORC pump
rec	Recovered
ref	Reference building
req	Required
s	Ideal isentropic case
t	ORC turbine

CHAPTER 1

INTRODUCTION

Combined heating and power (CHP) is the production of power (electrical or mechanical) and usable heat from a single fuel source. Often identified as cogeneration, CHP is a broad term referring to a set of integrated technologies such as turbines, reciprocating engines, microturbines, fuel cells, heat pumps, thermally activated technologies, and/or waste heat recovery technologies that can be implemented in different configurations to suit different needs. Thermally activated technologies transform thermal energy into useful heating, cooling, humidity control, thermal storage, and shaft/electrical power. Heat generated as a by-product from traditional, centralized power generation is typically lost to the atmosphere through cooling towers, flue gas, or other means, resulting in efficiencies near 35%. Over two-thirds of all the fuel used to generate power in the U.S. is lost as heat, see Figure 1.1. By placing the power production at or near the site of consumption, a form of distributed generation, CHP systems can use the would-be waste heat to satisfy some or all of the facility's thermal demand, which would otherwise be served by a boiler. Distributed generation also eliminates transmission and distribution losses associated with delivering electricity from the power plant to the customer. As illustrated in Figure 1.2, for the same electric and useful heat output, CHP systems consumes less fuel consumption than the separate production of electricity and heat, thereby reducing greenhouse gas emissions and

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lowering operational costs. Through waste heat utilization, CHP facilities are able to reach thermal efficiencies up to 80% [1], far superior than the combined efficiency of 45% for the separate production of electricity and usable heat.
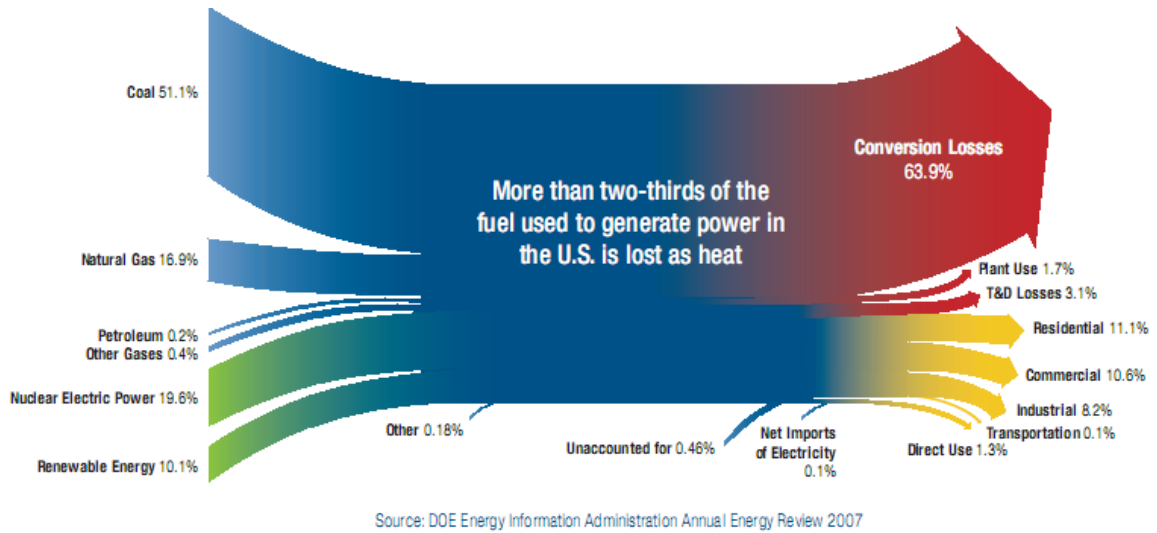
Figure 1.1   Electricity generation by source and consumption by sector [1]
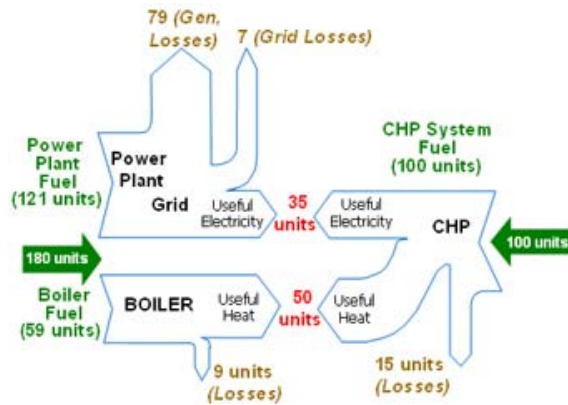
Figure 1.2   CHP versus separate production of electricity and useful heat [2]

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Aside from increased thermal efficiency, lower emissions, and lower operating costs, CHP installations help to ensure a robust energy infrastructure by reducing the demand on the current electric grid infrastructure and improving energy security. In addition, CHP systems are reliable sources of energy that can use a variety of fuel sources, including fossil fuels or renewable fuels. CHP systems are flexible and can be highly tailored to the needs of the user; and, unlike wind and solar-based energy systems, are not limited by geographic location.

Currently in the U.S., CHP systems account for 9% of the nation's power production. As indicated in Figure 1.3, this is very modest when compared to other countries. The U.S. Department of Energy (DOE) is leading the national effort to generate 20 percent of U.S. electricity with CHP by 2030 because in their view, "[CHP] provides a cost-effective, near-term opportunity to improve our nation's energy, environmental, and economic future [3]." The National Renewable Energy Lab (NREL) estimates that this increase could prevent 60% of the estimated potential growth in carbon dioxide emissions between 2006 and 2030 [3]. CHP technologies have the potential to make a dramatic impact on the future energy environment. The benefits of CHP installations are highly touted and well recognized throughout the world. Yet, there still exists barriers to more widespread implementation in the U.S. Along with technical barriers, several market conditions limit the full realization of CHP's potential. Challenges include "unfamiliarity with CHP, utility business practices, regulatory ambiguity, environmental permitting approaches that do not acknowledge and reward the energy efficiency and emissions benefits, uneven tax treatment, and interconnection

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requirements, processes, and enforcement [3]." Often, economics can be the governing factor that influences CHP system and current rates structures often reduce the money-saving potential of CHP systems thereby discouraging customer-owned CHP systems. For example, a number of U.S. utility rate structures are set up so that as more electricity is consumed, the average price per kWh decreases, providing an incentive to consume more electricity. In addition, the majority of the cost of service is often recouped in fixed charges and/or ratcheted demand charges. Furthermore, current ratemaking processes do not account for many of the societal benefits that CHP provides. Therefore, within this research actual utility rate structures are consider and compared to a constant price for electricity. In addition, benefits of a CHP system in terms of the Energy Star and LEED (Leadership in Energy and Environmental Design) programs are addressed. And finally, the use of carbon credits to place financial incentives on reduced emissions is examined.
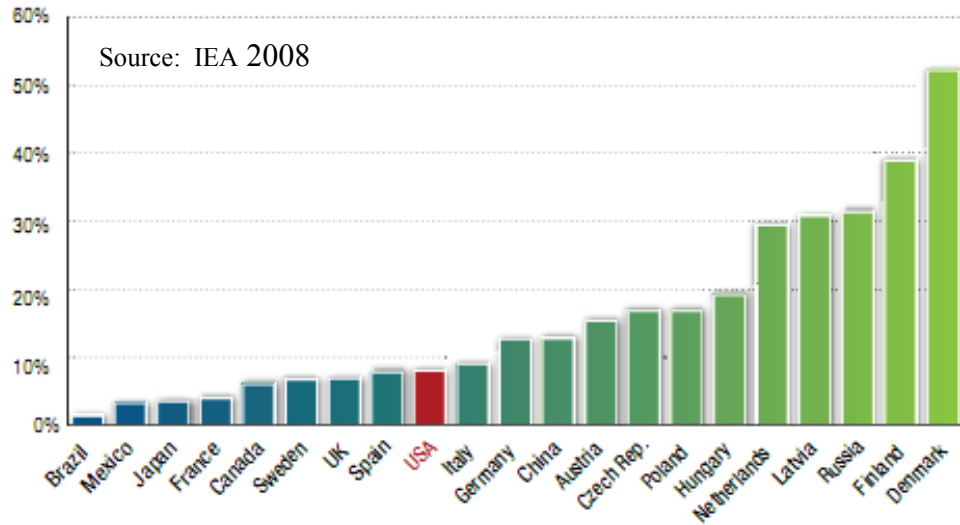
Figure 1.3   CHP capacity by country [1]

The sizes and applications of CHP systems vary to a considerable degree, ranging in size from a few kilowatts to megawatts of power production, with applications to residential, commercial, industrial, or large-scale district energy systems. The success of CHP systems is well proven in industrial and large scale applications. As seen in Figure 1.4, current CHP installation is primarily industrial applications. Large scale applications generally benefit from continuous and matching thermal and electrical loads, which results in better fuel utilization. More recently, the benefits of CHP systems for small scale commercial and residential applications are being investigated. Sometimes referred to as micro-CHP, the electric demand for these applications is generally less than 15 kW. The majority of this research focuses on applications for a small commercial office building.

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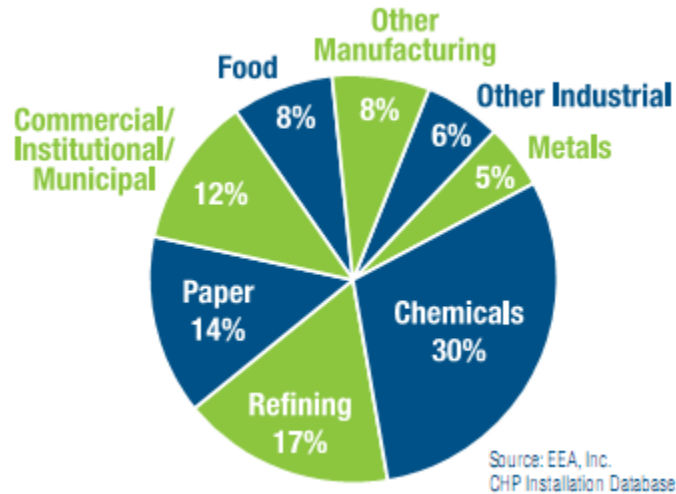
Figure 1.4   CHP installation by market [3]

Typical CHP systems are composed of a prime mover and generator, together termed the power generation unit (PGU), a heat recovery system, and thermally activated technologies. The prime mover in CHP systems converts fuel to power; typical examples include gas turbines, microturbines, internal combustion engines, Stirling engines, and fuel cells. Natural gas is the most common fuel source, representing 50–80 percent of annual CHP capacity additions since 1990 [1]. This is primarily because natural gas is clean burning and has historically been relatively plentiful, available, and affordable. Thermally activated technologies, driven by exhaust heat captured from the PGU, can produce hot water, supply process heat or space heating, provide space cooling, or dehumidify process air through the use of desiccant materials. Often the usable heat is used for cooling and air conditioning applications, typically in an absorption chiller, adsorption chiller, steam chiller, or a desiccant dehumidification unit, and, in these cases, the arrangement can be referred to as combined cooling, heat, and power (CCHP) or trigeneration, which can be considered a type of CHP technology.

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The following chapter provides additional details that are related to the current study through a literature survey. This leads into an outline and overview of the dissertation objectives.

CHAPTER 2

LITERATURE REVIEW

CHP systems are not a one size fits all technology. The timing, magnitudes, and types of energy demanded (electricity, mechanical power, heating, cooling, etc.) by the facility are generally unique and can depend on the application (hospital, supermarket, ice rink, etc.) and also on the location (due to the weather). Therefore, modeling of CHP systems plays a crucial role in assessing different CHP configurations, operational strategies, and novel technologies. In addition, models aide in the analysis of existing systems, allowing the system's performance to be gauged.

Khan et al. [4] presented modeling, experimentation, and optimization of a novel CCHP system for power, water extraction, and refrigeration. The system combined a semi-closed Brayton cycle with pressurized recuperation and integrated with a vapor absorption refrigeration system. Malico et al. [5] designed a CCHP system that used a high-temperature fuel cell to meet the electric load of a hospital coupled with an absorption cycle and supplemental boiler. Although the thermal efficiency was 68%, the system was not financially feasible. Moran et al. [6] presented simulation results from CCHP systems that used natural gas and diesel internal combustion engines as the prime mover. The system efficiency for cooling months was found to reach values up to 80% with economic feasibility highly dependent on fuel prices. Ren et al. [7] developed a mixed integer nonlinear programming model of a residential CHP system located in

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Japan that consisted of a CHP plant, a storage tank, and a back-up boiler. The model selects the optimal capacity of the CHP prime mover, storage tank, and back-up boiler along with the optimal hourly operating strategy based on an objective function that minimizes the annual overall cost of the CHP system. A single, flat-rate price for electricity and natural gas was used to determine operating costs and capital costs were also considered.

The prime mover and its method of operation inherently influence the performance of CHP systems. For example, based on a thermoeconomic analysis of a trigeneration system, Temir and Bilge [8] found the prime mover (an engine) to have the lowest exergy efficiency among the system components. Nayak et al. [9] designed and built a CHP system integrated with a liquid desiccant dehumidification system for a medium sized office (52,000 ft^2). They found that, unlike the electrical efficiency of the engine which is greater at full load, the efficiency of the CHP system is actually higher while operating at part load rather than at full load. This is because although the engine efficiency decreases with the load, the amount of waste heat recovered at part load is only slightly lower in comparison to the full-load condition.

Two common operational strategies for CHP and CCHP systems are to follow the electric load (FEL) and to follow the thermal load (FTL). Under FEL operation, the goal of the prime mover is to meet the electricity load for the building and the exhaust heat is a by-product. Following the electric load minimizes excess generated electricity. For FTL, the prime mover aims to produce the heat demanded by the building, thereby minimizing any wasted heat. During this strategy the generated electricity is a by-product of heat

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production. Jalalzadeh-Azar [10] investigated a thermal-load-following gas-fired mircoturbine CCHP system for a hypothetical office building (19,500 ft^2) in Atlanta and compared the results to a previous study, Jalalzadeh-Azar [11], which evaluated a grid-independent electrical-load-following CCHP system. For both models, thermal- and electrical-load-following, a parametric analysis was performed to examine the influence of the subsystem efficiencies on the overall system performance, without consideration for costs. For the FTL model, the total capacity of the system was sized to meet the thermal demand with the assumption that excess electricity could be exported to the grid. The parametric analysis for both models revealed that improving the on-site power generation efficiency resulted in significant reductions in total energy consumption; however, this effect was not as pronounced when improving the absorption cooling efficiency. Through an evaluation of first law efficiencies for the two models, the thermal-load-following model was found to have a considerably higher CCHP system efficiency, due to higher waste heat utilization, which also resulted in a higher overall efficiency.

Mago et al. [12] compared FEL and FTL strategies for both CHP and CCHP systems that used an internal combustion engine as the prime mover for a small office (1,500 ft^2) in four different climate regions. Comparisons were made based on primary energy consumption, cost, and carbon dioxide emissions. A national average primary energy consumption factor for electricity was used to determine the primary energy consumption. Cost was figured from a single flat rate for both electricity and natural gas. The calculated carbon dioxide emissions depended on the regional mix of fuel used to

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produce grid electricity. Mago et al. [12] found that, in general, FTL performed better than FEL. In another study, Mago and Chamra [13] optimized CCHP systems that were operated under FEL and FTL strategies based on energy, cost, and emissions. In addition, they evaluated an optimized operational strategy in which a CCHP system follows a hybrid electric–thermal load strategy.

Cardona and Piacentino [14] investigated the sizing and management of trigeneration plants for hotels in the Mediterranean area. They compared a thermal load following strategy, thermal demand management (TDM), to the positive energy savings management criteria (PES), which is an original criterion proposed by the authors with the aim of maximizing energy savings during the plant life. TDM often results in a rather low load level; but, by increasing the load energy savings are still possible, although slightly less than that for TDM. This would allow for a better plant choice, thus enhancing the energy savings throughout the whole plant life. The most common plant choice (sizing) method based on the thermal consumption cumulative curve is described and then compared to an original choice method based on PES. Assuming electricity could be sold back, the proposed criterion significantly augments the annual amount of energy that is actually "cogenerated." Similarly, Cardona et al. [15] modeled CHP systems based on TDM and Electric Demand Management (EDM). The prime mover loading as well as a few extraneous circumstances, such as the ability to sell electricity to the grid or store it on site for later use, was found to dictate the choice between EDM and TDM. In addition, the price of fuel versus that of grid electricity can affect the management of a plant.

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Other operational strategies rely on objective functions and attempt to minimize parameters such as cost, primary energy, emissions, or exergy. Hawkes and Leach [16] compared a "least cost" operating strategy for a UK residential micro-CHP to heat-led and electricity-led operation. Operational costs along with carbon dioxide emissions were determined for three different prime mover technologies: a Stirling engine, a gas engine, and a solid oxide fuel cell, all of which had a fixed capacity of 2 kW_e and capable of thermal energy storage. Operational costs and emissions were determined using national average domestic costs and national average grid emission rates. All the technologies and all the operating strategies reduced operating costs over the baseline case of just grid electricity and a boiler. Emissions were improved in all the cases except the Stirling engine and electricity-led gas engine. For the two engines, the least cost operating strategy did not coincide with the strategy yielding the lowest emissions, which was heat-led. The least-cost results were very sensitive to the electricity buyback rate and the time of year. In general, though, the best operational strategy shifted from electric-led to both electric- and heat-led to heat-led as the buyback rate increased. Due to the low percentage of load met by the grid (about 30% for the gas engine) and boiler (about 20% for the gas engine), the operational dispatch was not sensitive to increases in the electricity and natural gas import prices.

Other researchers have investigated the use of a turbine prime mover for CCHP applications. Savola and Keppo [17] modeled four existing steam turbine CHP systems (1-20 MW_e) operating at part load. They found that although the part-load power production can be described quite accurately with a single, nonlinear curvefit, there is a

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small nonlinear reduction in the power production as the heat load decreases. Kong et al. [18] presented a simple linear programming model to determine the optimal strategies that minimize the overall cost of energy for the CCHP system. The energy system consisted of a gas turbine, an absorption chiller, and a heat recovery boiler. The optimal system operation was found to depend upon the load conditions being satisfied. They also reported that for the case of a low electric-to-gas cost ratio, operating the turbine might not be optimal. Khan et al. [4] presented a novel cooling and power cycle that combined a semi-closed gas turbine cycle with a vapor absorption refrigeration system for power, water extraction, and refrigeration. The combined cycle efficiency was found to be 44%. Colombo et al. [19] presented and discussed the results of an experimental investigation of a microturbine cogeneration plant. Experimental tests were run on a Turbec T100-CHP microturbine unit while varying the electrical power output between 50 and 110 kW and for water temperatures varying from 60 to 80°C at the recuperator outlet. They reported that the performance remain essentially constant in the range of 80–110 kW while a moderate decrease was observed from 50 to about 60 kW.

Chicco and Mancarella [20] introduced a generalized indicator for the fuel savings of any kind of trigeneration plant. Essentially an extension of the fuel energy savings ratio (FESR), the trigeneration primary energy savings (TPES) compares the fuel used by the trigeneration of electricity, heating, and cooling to the fuel needed to separately produce the same energy. A case study was presented where values of the TPES index were computed over one year for different load scenarios, cooling alternatives, operational strategies, and separate production efficiency scenarios.

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Separate production efficiency scenarios (low efficiencies, average efficiencies, or state-of-art) were found to affect both the energy savings and the most effective plant and operation strategy. Assuming fixed separate production efficiencies, the most suitable trigeneration plant configuration, in terms of energy savings, depends on the expected loading level.

Sun [21] evaluated a CCHP system consisting of a gas engine, a generator, and an absorption refrigeration system that produced chilled water or hot water depending on the demand. In terms of primary energy, the CCHP system was found to be superior to a conventional system (vapor compression for cooling and boiler for heating). An economic analysis of the system determined the payback period while considering capital costs, operation costs, maintenance costs, fuel price, and the price of electricity purchased and sold. The payback period was 4.52 years with the main influential factors being the natural gas price and electricity price. Higher natural gas prices or lower electricity prices increased the payback period. In this study, like other CCHP and CHP models and optimization schemes, a constant value was used for the price of electricity and natural gas during the economic analysis.

Organic Rankine cycles recover exhaust heat to generate power. By producing power from exhaust heat that would otherwise go unused, the addition of an ORC to a CHP system can reduce the fuel consumption of the standalone CHP system which will lower the associated cost of operation and emissions. By using an organic working fluid, the Rankine cycle can produce power from low-temperature heat (80-370°C) and the thermal efficiency of the cycle becomes economically feasible [22]. At these low

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temperatures, a steam cycle would be inefficient because of the enormous requirement for low pressure steam, thereby causing voluminous and costly plants. Examples of low-grade heat sources are industrial waste streams, solar heat, engine cooling water, engine exhaust, geothermal, among others. Due to the abundant nature of these heat sources, more and more attention is being given to the utilization of low-grade waste heat due to its potential to reduce fossil fuel consumption and to lessen the environmental impact of energy generation.

Chacartegui et al. [22] studied a low-temperature ORC as a bottoming cycle in medium- and large-scale combined cycle power plants. Their analysis illustrated how an ORC can be used with high efficiency, heavy-duty gas turbines using different organic fluids: R113, R245, isobutene, toluene, cyclohexane and isopentane. Al-Sulaiman et al. [23] used an exergy analysis to evaluate a combined solid oxide fuel cell (SOFC) and ORC for cooling, heating and power production (500 kW$_e$). The exergy efficiency for the power cycle increased from 3 to 25% when trigeneration was used compared with the power cycle alone. Similarly, Akkaya and Sahin [24] found that the addition of an ORC to an SOFC with a net electric output of 300 kW increased the first law efficiency by 14%.

The type of working fluid and its physical properties affect the performance of the ORC. Dai et al. [25] evaluated and optimized the use of ORCs for low-grade heat recovery using different working fluids. Their results showed that the cycles with organic working fluids are better than the cycles with water in converting low-grade heat to useful work. Mago et al. [26] presented first- and second-law analysis for the

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following working fluids in an ORC: R113, R123, R245ca, R245fa, isobutene, propane, and R134a. The effect on the thermal efficiency and irreversibility of an ORC for the above working fluids was determined while varying operating parameters. The results demonstrated that an ORC using R113 produced the maximum efficiency among the evaluated organic fluids. In another investigation, Mago et al. [27] presented an analysis of a regenerative ORC using the dry organic fluids R113, R245ca, R123, and isobutene.

Although several studies have been performed on CHP systems, standalone ORCs, and CHP plants based on an ORC, the use of an ORC as a supplement of CHP systems to produce extra power from any unused heat of the CHP system for small-scale applications is subject to further investigation. Therefore, one objective of this paper is to study the energetic, economical, and environmental performance of a combined CCHP system and ORC (CCHP-ORC) and a combined CHP system and ORC (CHP-ORC) for a small office building.

The next section on non-traditional benefits of CHP systems presents an overview of the Energy Star and LEED programs along with a description of carbon credits. Subsequently, the small and large office buildings are described. The following chapters, Chapter 5 and 6, give the schematics and descriptions, mathematical models, and operational strategies pertaining to the different CHP systems used throughout the dissertation. In Chapter 7, the performance metrics of cost, primary energy consumption, and carbon dioxide emissions are defined and then optimizations schemes based on these metrics are presented. The results are present and discuss in Chapters 8 through 11, which are titled

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8. A review of the economical, energy, and environmental benefits of CHP and CHP-ORC systems

9. Influence of prime mover size and operational strategy on the performance of CCHP and CHP systems under different cost structures

10. Analysis and optimization of a CCHP-ORC system and a CHP-ORC system for a small commercial office building

11. Evaluation of a turbine driven CCHP system for a large office building under different operating strategies

Lastly, Chapter 12 presents the conclusions.

The majority of this research, Chapters 8 through 10, focuses on the less commonly studied small commercial office building for CHP applications. For these studies, a natural gas internal combustion engine is chosen as the prime mover and instead of simulating a hypothetical building, a benchmark building of a small office developed by the Department of Energy is used.

Chapter 8 examines the operational costs, primary energy consumption, and carbon dioxide emissions for a CHP and CHP-ORC system in different North American climates. Also, the performance of each system operating 24 hours a day was compared to the system operating during typical office hours. The benefits of the CHP system based on the Energy Star program and the LEED program will be presented. The CHP-ORC system's ability to reduce the amount of electricity that must be generated by the PGU of the CHP system and the subsequent effect on the total fuel consumption is evaluated.

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Chapter 9 evaluates the role of the prime mover in the performance of CCHP and CHP systems under different cost structures. For this study, the systems are simulated using three different engine sizes operating under different constant loads in addition to FEL and FTL strategies. To measure the performance of the system annual operational cost, primary energy consumption, and carbon dioxide emissions are determined and compared to a reference building operating under conventional technologies. In computing costs, actual electric rates were used along with historical monthly natural gas rates. Three cities with different electricity rate schedules were chosen for analysis: Boulder, CO, where a constant rate exists; Duluth, MN, where seasonal rates are present; and Chicago, IL, which incorporates block charges. Finally, the performance of the systems is improved through a simple optimization that minimizes cost, primary energy, or carbon dioxide emissions. For the CCHP system, comparisons are made between the predicted costs using real cost data to those calculated using average rates. Moreover, operational costs are determined for different electricity exporting prices. Finally, comparisons between the CCHP and CHP systems are presented.

Chapter 10 extends Chapter 9 to include CCHP-ORC and CHP-ORC systems. The use of an ORC to improve the system's performance is demonstrated and comparisons are made to the reference building and across system configurations.

Lastly, Chapter 11 investigates a load-share turbine as the prime mover in a CHP system for use in a large office building. The CCHP system is evaluated under three different operation strategies: following the electric demand of the facility, following the thermal demand of the facility, or following a seasonal strategy. As was done in the

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previous studies, the primary energy consumption, operational costs, and carbon dioxide emissions are determined with respect to a reference building using conventional technologies. Other objectives of this paper are to determine the percentage of emissions generated from the delivered electricity and the on-site electricity production and to illustrate how reductions in carbon dioxide emissions obtained from operation of the CCHP system can translate into economic benefits using carbon credits. Real electricity and natural gas rates for the evaluated city are considered. This is accomplished by simulating the CCHP system in the city of Chicago, which incorporates block charges and demand charges in their utility schedule. Actual monthly gas rates for Illinois were also employed to account for the variations in gas rates across locations and fluctuations in prices throughout the year. Finally, for a given payback period and operational cost savings of the CCHP system, the capital cost available to invest in the CCHP system is determined.

CHAPTER 3

NON-TRADITIONAL BENEFITS OF CHP SYSTEMS

3.1   Energy Star and LEED Programs

Two building energy-rating systems are recognized for benchmarking buildings in

the U.S., Energy Star[1] and LEED[2]. Improvements offered by CHP systems in building

energy performance can be evaluated using the Energy Star rating system [28]. A rating

scale of 1 to 100 marks the performance of the building with respect to other, similar

types of buildings. A score of 75 indicates that the building's performance is in the top

25% of its peer group. Buildings achieving a rating of 75 or higher with a healthy and

productive indoor air environment, consistent with industry standards, are eligible to

receive the Energy Star label. According to the Energy Star program, displaying an

Energy Star plaque conveys superior energy performance to tenants, customers, and

employees.

As a national program for protecting the environment through superior energy

efficiency, Energy Star uses primary energy (or source energy) as the basis for

benchmarking building energy performance. The building's actual source energy data

are weather normalized, which assesses the building performance relative to the typical

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[1] Energy Star is a joint program of the U.S. Environmental Protection Agency (EPA) and the U.S.
Department of Energy (DOE) helping businesses and individuals save money and protect the environment
through energy efficient products and practices.
[2] The LEED Green Building Rating System is a program developed by the U.S. Green Building Council
(USGBC) that provides a suite of standards for environmentally sustainable construction.

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weather for the corresponding region. The Energy Star program offers energy management strategies and tools to help improve and track energy performance. To evaluate the energy performance for design projects and major building renovations, the program offers a web-based tool called Target Finder [29].

A CHP system can also be an important contributor toward a LEED certification. To achieve LEED certification, buildings must meet all prerequisites in the rating system and have a minimum of 40 points. LEED for Existing Buildings (LEED-EB) certification is awarded according to the following point thresholds: Certified (40–49 points), Silver (50–59 points), Gold (60–79 points), and Platinum (80 points and above) [30]. The categories that are evaluated and the respective possible points are: Sustainable Sites (26 points), Water Efficiency (14 points), Energy and Atmosphere (35 points), Materials and Resources (10 points), Indoor Environmental Quality (15 points), Innovation in Operations (6 points), and Regional Priority (4 points). Within the Energy and Atmosphere category, Credit 1: Optimize Energy Performance has the greatest possible weight, with 1–18 available points, and is based on the U.S. Environmental Protection Agency's (EPA) Energy Star performance rating using Target Finder. An Energy Star rating higher than 71 acquires points according to Table 3.1 [30].

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Table 3.1   Points available for the LEED-EB certification due to the Energy Star rating (Adapted from [30])

Energy Star Rating	LEED-EB Points
71	1
73	2
74	3
75	4
76	5
77	6
78	7
79	8
80	9
81	10
82	11
83	12
85	13
87	14
89	15
81	16
93	17
95	18

To determine the Energy Star rating, the site energy consumption, the amount of fuel and electricity consumed by a building as reflected in utility bills were used as inputs for the Target Finder tool. The steps required to determine the rating using Target Finder for a small office building are described below:

Step 1: Input the zip code where the office is located. This determines the climate conditions that the building would experience in a normal year.

Step 2: Input the office gross floor area, occupants, number of PCs, and operating hours/week.

Step 3: Input the reference office's annual electricity and fuel consumption and the tool will provide the rating value.

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After determining the Energy Star rating, the points available for the LEED-EB certification can be determined using Table 3.1.

3.2   Carbon Credits

The purpose of carbon credits is to create economic value from defined environmental benefits such as the reduction of greenhouse gas (GHG) emissions, which include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs). When compared to a conventional building, the use of a CHP system can reduce the amount of emissions and therefore gain some economic benefits using carbon credits. One of the methodologies suggested to address GHG emissions is a market-based "cap and trade" system. For companies and industries that significantly contribute to GHG emissions, direct emitters, a cap or limit is placed on the amount of allowable emissions. These companies or industries must reduce their emissions to a level equal to or below the cap. If their emissions are below the target they are issued credits. Those who cannot meet the cap must purchase credits, thus bringing their emissions into compliance with the cap. In addition to direct emitters, indirect emitters such as office-based businesses or industries generate emissions indirectly through the consumption of electricity and other related activities. These types of companies must offset 100% of their emissions by purchasing credits. This ensures that the atmospheric burden of greenhouse gases (GHGs) is not increased by the entity's indirect activities. Chicago Climate Exchange (CCX) uses such a system, which is currently a voluntary but legally binding commitment for its members [31]. For many companies reducing emissions is an important part of their business

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philosophy, and joining CCX provides credible evidence that highlights their leadership and accomplishments in reducing their harmful impact on the environment. In addition, members of CCX gain experience in emissions management and will be prepared for future policies involving GHG regulations. In this investigation, only carbon dioxide emissions are considered. To offset carbon dioxide emissions "carbon credits" must be purchased, which are typically priced in dollars per metric ton of CO_2-equivalent (\$/t of CO_2-equivalent).

CHAPTER 4

REFERENCE BUILDINGS

The buildings used in this study are a small and large office building taken from the U.S. Department of Energy's benchmark building models [32]. The DOE developed sixteen types of benchmark models for sixteen different locations, which represent approximately 70% of the new commercial buildings in the U.S. [33]. The models are available as input files to EnergyPlus [34], which is software designed to do whole building energy simulations. For each location considered in this study, the benchmark building was simulated in EnergyPlus and used as the reference case. From the simulation results, the building's electric, cooling, heating, and hot water loads were determined and used for the CHP and CCHP system analyses. In the reference case, electricity imported from the grid is used for lights, equipment, and HVAC components. In addition, the boiler consumes natural gas to satisfy the heating and hot water loads of the building.

The small office is a rectangular, single-story 5,500 ft^2 building displayed in Figure 4.1. A packaged air conditioning unit that operates on grid electricity provides cooling through a single zone, constant-volume air distribution. Table 4.1 presents the small office building characteristics. The energy consumption of the small office reference case depends on its location, but across all sixteen locations, the average annual electricity use is 72,689 kWh and the average annual gas use is 84,144 J (0.023373 kWh).

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	(a)	(b)
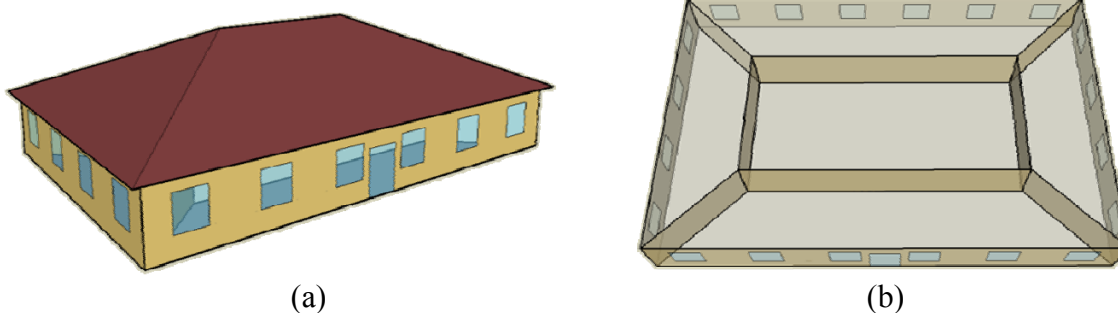
Figure 4.1   Small office building (a) exterior and (b) interior zones [35]

Table 4.1   Characteristics of the reference buildings [35]

	Small Office	Large Office
Floor area (ft^2)	5,500	498,584
Number of floors	1	12 plus basement
Cooling system	Vapor compression	Water-cooled electric chiller
Fan control	Constant volume	Variable air volume
COP	3.05	5.5
Heating system	Gas furnace	Gas boiler
Heating efficiency (%)	80	78
Water heating system	Gas water heater	Gas boiler
Water heating thermal efficiency (%)	80	80

The large office is a 498,584 ft^2, 12 story plus a basement building shown in Figure 4.2. An electric chiller unit provides cooling, and the air distribution is through a multi-zone variable air volume system. The large office building characteristics are presented in Table 4.1. The only location evaluated for the large office building is Chicago, IL. Figure 4.3 presents the monthly electric (not including the electricity for the chiller), cooling, heating, and hot water loads for the reference building. These loads were determined from the EnergyPlus simulation.

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| (a) | (b) |
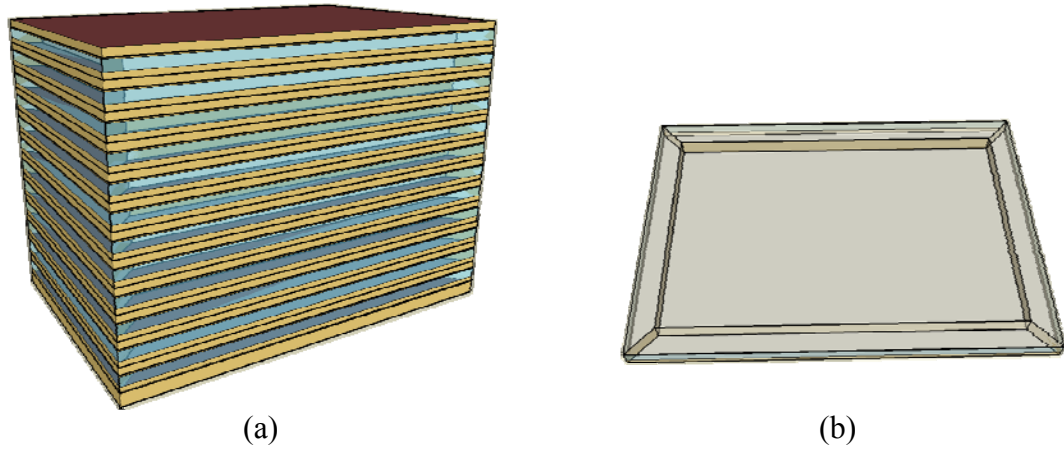
Figure 4.2   Large office building (a) exterior and (b) interior zones [35]
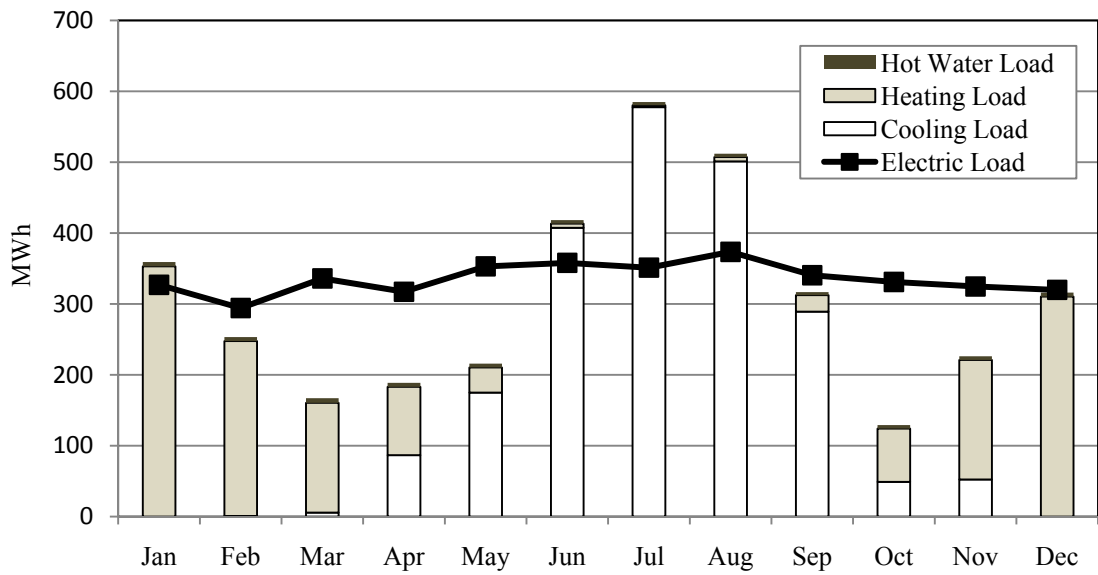
Figure 4.3   Electric, cooling, heating, and hot water loads for the large office
building located in Chicago, IL

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CHAPTER 5

CHP AND CCHP SYSTEMS

This chapter introduces the CHP and CCHP configurations used in this study. Then, the model descriptions for each system are given. Finally, the different operational strategies for the systems are explained.

The CHP system modeled in this study for the small office building is pictured in Figure 5.1. For the large office building, the vapor compression system is replaced with an electric chiller. The power generation unit (PGU) (prime mover and generator) produces electricity to satisfy the building's electric demand and the exhaust heat is recovered and used by the heating coil to meet the building's heating load and/or the hot water system to supply hot water. The office building is connected to the grid to supply electricity if the PGU cannot meet the electric load. In addition, excess electricity generated by the PGU can be exported back to the grid. When the exhaust heat is not enough to meet all the building's thermal needs, an auxiliary boiler is present to provide additional heat.

The CCHP system used in this study is presented in Figure 5.2. This system uses an absorption chiller to provide cooling for the building as opposed to the vapor compression system in the CHP system. The absorption chiller is heat driven and operates from heat produced by the engine and/or boiler.

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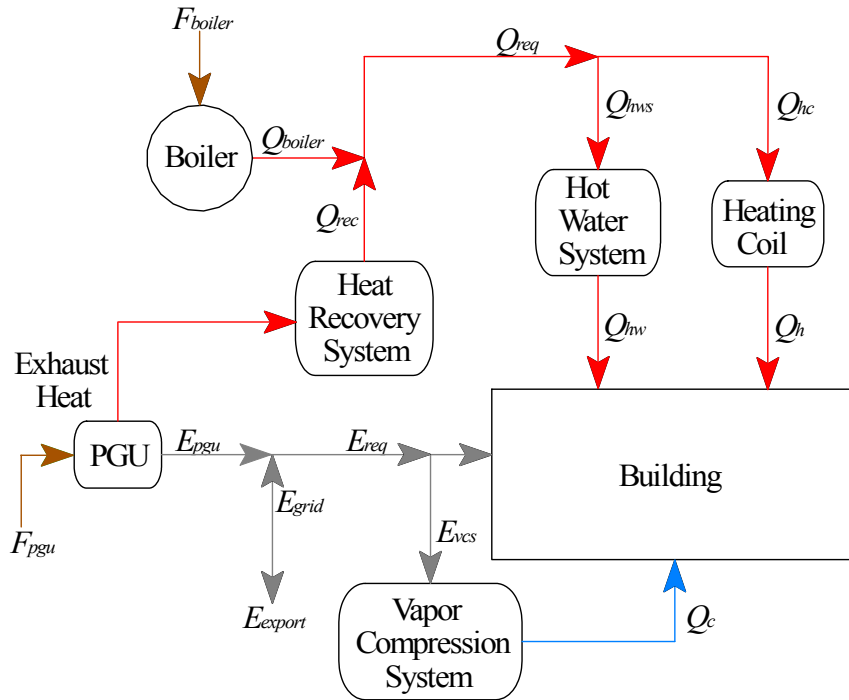
Figure 5.1   CHP system schematic for small office building
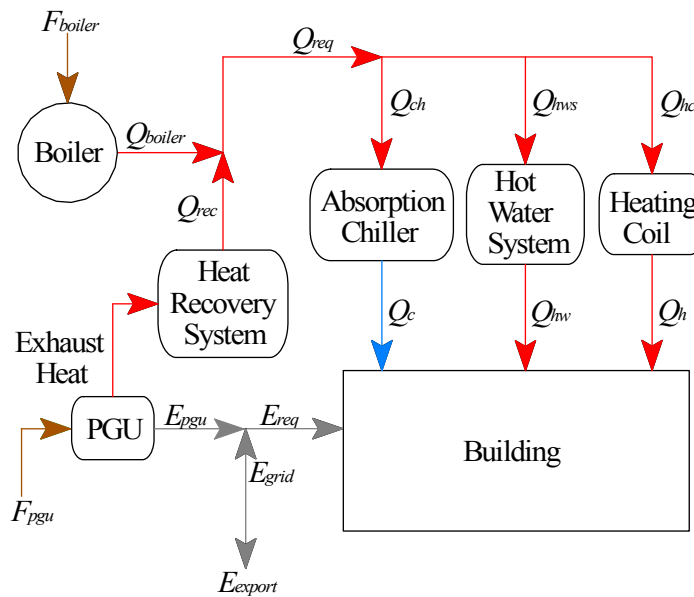
Figure 5.2   CCHP system schematic

The following sections outline the methods used to model the CHP and CCHP systems. In both cases, the system was simulated hour-by-hour for a year. The loads required by the building were determined by simulating the reference building in EnergyPlus for a particular location. These include the building's electric load, E_{req}, heating load, Q_h, cooling load, Q_c, and hot water load, Q_{hw}.

5.1 CHP System Model

The building's electricity requirements is composed of the electricity needed to operate the lights, E_{lights}, equipment, $E_{equipment}$, vapor compression system, E_{vcs}, and HVAC fans, E_{fans}. For each hour, the CHP system and/or the grid must satisfy the electric load of the building, E_{req}, which is

$$E_{req} = E_{lights} + E_{equipment} + E_{vcs} + E_{fans} \qquad (5.1)$$

To meet the building's thermal load, a certain amount of heat is required to operate the heating coil (Q_{hc}) and the hot water system (Q_{hws}). Therefore, the hourly heat required from the recovered PGU exhaust and or the boiler is

$$Q_{req} = Q_{hc} + Q_{hws} \qquad (5.2)$$

where $Q_{hc} = Q_h/\eta_{hc}$ and $Q_{hws} = Q_{hw}/\eta_{hws}$ for heating coil and hot water system thermal efficiencies of η_{hc} and η_{hws}, respectively.

The operational strategy, discussed later, will dictate the hourly electrical output of the PGU, E_{pgu}. If the electric output of the PGU is less than the required electric load of the office, grid electricity must be imported. Conversely, if the PGU generates more electricity than is required, the excess may be exported to the grid. Therefore,

$$E_{grid} = \begin{cases} E_{req} - E_{pgu} & \text{if} & E_{pgu} < E_{req} \\ 0 & \text{if} & E_{pgu} \geq E_{req} \end{cases} \tag{5.3}$$

$$E_{export} = \begin{cases} E_{pgu} - E_{req} & \text{if} & E_{pgu} > E_{req} \\ 0 & \text{if} & E_{pgu} \leq E_{req} \end{cases} \tag{5.4}$$

The option to export electricity, especially for small applications, may not be available.

For an internal combustion engine as the prime mover, the fuel (natural gas) consumption of the PGU is determined from the following curve fit [36]

$$F_{pgu} = \begin{cases} 0 & \text{if} & E_{pgu} < E_{min} \\ \alpha * E_{pgu} + \beta & \text{if} & E_{pgu} \geq E_{min} \end{cases} \quad \text{where} \quad E_{min} > 0 \tag{5.5}$$

where E_{min} is the minimum output of the prime mover and α and β are constants obtained from manufacturer's data and depend on the engine size. The efficiency of the engine can be comuputed using the following equation

$$\eta_{pgu} = \frac{E_{pgu}}{F_{pgu}} \tag{5.6}$$

where an example of the resulting engine efficiency vesus power output curve is presented in Figure 5.3. For the engine, the minimum electric output was taken to be 25% of the full-load output.

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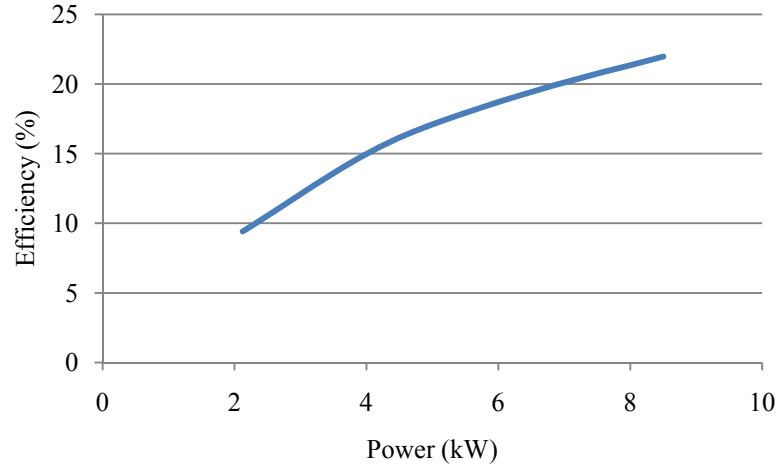
Figure 5.3   Efficiency versus power performance curve for an internal combustion engine

For the load-share turbine, the fuel consumed by the PGU is calculated from the PGU efficiency, η_{pgu}, according to

$$F_{pgu} = \frac{E_{pgu}}{\eta_{pgu}} \tag{5.7}$$

The thermal efficiency of the load-share turbine used in this study is presented in Figure 5.4 and modeled using the following curve fit data

$$\eta_{pgu} = \begin{cases} aE_{pgu}^4 + bE_{pgu}^3 + cE_{pgu}^2 + dE_{pgu} + e & \text{if } 0 < E_{pgu} \le 200 \text{ kW} \\ a'E_{pgu}^2 + b'E_{pgu}^2 + c' & \text{if } 200 \text{ kW} < E_{pgu} \le 400 \text{ kW} \\ a''E_{pgu}^2 + b''E_{pgu}^2 + c'' & \text{if } 400 \text{ kW} < E_{pgu} \le 600 \text{ kW} \\ a'''E_{pgu}^2 + b'''E_{pgu}^2 + c''' & \text{if } 600 \text{ kW} < E_{pgu} \le 800 \text{ kW} \end{cases} \tag{5.8}$$

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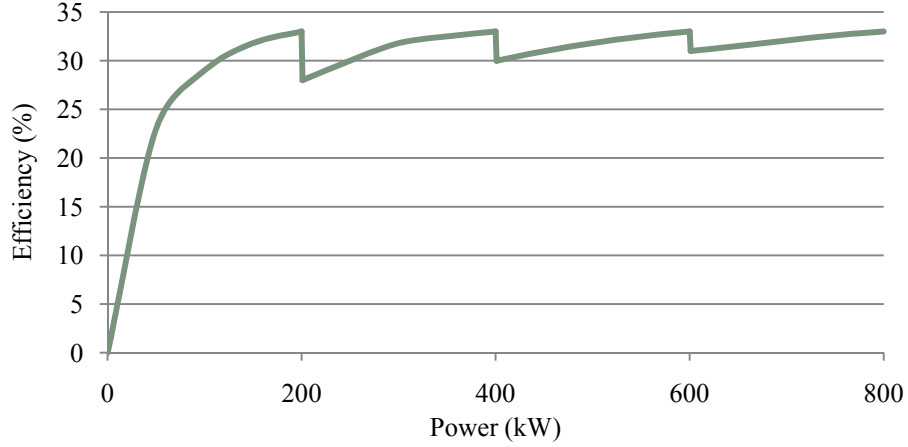
Figure 5.4　　　Efficiency versus power performance curve for a load-share turbine (Adapted from [37])

The boiler operation and, therefore, the natural gas consumption of the boiler, depends on whether the PGU can satisfy the required thermal needs of the building. The heat recovered from the PGU, Q_{rec}, is

$$Q_{rec} = \eta_{rec}(F_{pgu} - E_{pgu}) \tag{5.9}$$

where η_{rec} is the efficiency of the heat recovery system. If the recovered heat is less than the required heat, the boiler must make up the difference, so

$$Q_{boiler} = \begin{cases} Q_{req} - Q_{rec} & \text{if} \quad Q_{req} > Q_{rec} \\ 0 & \text{if} \quad Q_{req} \leq Q_{rec} \end{cases} \tag{5.10}$$

The amount of fuel needed by the boiler is then

$$F_{boiler} = \frac{Q_{boiler}}{\eta_{boiler}} \tag{5.11}$$

where η_{boiler} is the thermal efficiency of the boiler. For the investigation using a load-share turbine as the PGU, the boiler thermal efficiency is ploted in Figure 5.5 and modeled using the following curve fit

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$$\eta_{boiler} = Ax^2 + Bx + C \qquad (5.12)$$

where x is the air and fuel input expressed as a percent of the maximum input.
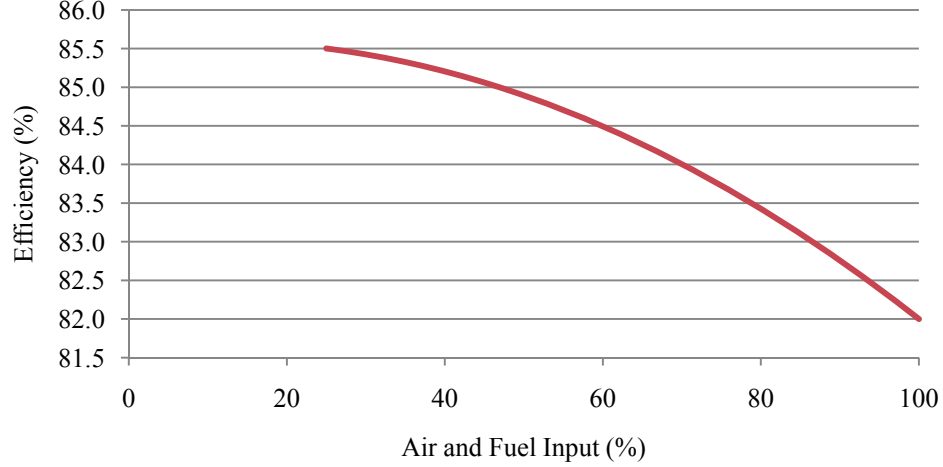
Figure 5.5   Boiler efficiency performance curve as a function of air and fuel input (Adapted from [38])

5.2   CCHP System Model

Operation of the CCHP system, shown in Figure 5.2, is similar to that of the CHP system, but under the CCHP system, the cooling demand is satisfied by an absorption chiller.   Shifting the cooling production from electricity driven (vapor compression system or electric chiller) in the CHP system to heat driven in the CCHP system (absorption cycle) changes the amount of electricity required by the building and the amount of heat needed from the PGU exhaust and/or boiler.   The resulting amount electricity that must be provided by the CCHP system and/or the grid for each hour is

$$E_{req} = E_{lights} + E_{equipment} + E_{fans} \qquad (5.13)$$

For each hour, the heat that must be recovered from the PGU exhaust and/or delivered by the boiler now includes that the heat required by the absorption chiller, Q_{ch}, and is

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$$Q_{req} = Q_{hc} + Q_{ch} + Q_{hws} \tag{5.14}$$

where Q_{ch} is determined from the cooling load and the absorption chiller coefficient of performance, COP_{ch}. Accordingly, $Q_{ch} = Q_c/COP_{ch}$. Equations (5.3) through (5.11) can then be used to determine the CCHP system fuel and grid consumption, as was done for the CHP system.

5.3   Operational Strategies

For this study, the operational strategies (aside from optimization) for the CHP and CCHP systems are:

- o   follow the electric load (FEL)

- o   follow the electric load with cutoff (FELc)

- o   follow the thermal load (FTL)

- o   follow the thermal load with cutoff (FTLc)

- o   follow a seasonal strategy (FSS)

- o   follow a constant load

The FEL, FTL, FSS, and constant load strategies operate continuously and the prime mover never cuts off. For the cutoff strategies, when the CHP system is off, electricity will be imported from the grid to satisfy the electric demand and the boiler will solely satisfy the thermal demand.

To follow the electric load, the PGU will always try to meet the building's required electricity needs and, therefore, run continuously, so for FEL

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$$E_{pgu} = \begin{cases} E_{min} & \text{if} & E_{req} < E_{min} \\ E_{req} & \text{if} & E_{min} \leq E_{req} < L \\ L & \text{if} & L \leq E_{req} \end{cases} \qquad (5.15)$$

With cutoff, the PGU will shut off if the required electric load if below the minimum load, therefore for FELc

$$E_{pgu} = \begin{cases} 0 & \text{if} & E_{req} < E_{min} \\ E_{req} & \text{if} & E_{min} \leq E_{req} < L \\ L & \text{if} & L \leq E_{req} \end{cases} \qquad (5.16)$$

Similarly, to follow the thermal load, the PGU will try to generate enough heat so that $Q_{req} = Q_{rec}$. Using Equations (5.5) and (5.9) to expand this equality, the PGU electric output that is needed to satisfy the required heating, $E_{Q_{req}}$, is

$$E_{Q_{req}} = \frac{Q_{req}/\eta_{rec} - \beta}{\alpha - 1} \qquad (5.17)$$

The PGU electric output under FTL operation is then

$$E_{pgu} = \begin{cases} E_{min} & \text{if} & E_{Q_{req}} < E_{min} \\ E_{req} & \text{if} & E_{min} \leq E_{Q_{req}} < L \\ L & \text{if} & L \leq E_{Q_{req}} \end{cases} \qquad (5.18)$$

For FTLc, the engine will shut off if the required heat is below the minimum amount of heat that can be recovered from the engine, or

$$E_{pgu} = \begin{cases} 0 & \text{if} & E_{Q_{req}} < E_{min} \\ E_{req} & \text{if} & E_{min} \leq E_{Q_{req}} < L \\ L & \text{if} & L \leq E_{Q_{req}} \end{cases} \qquad (5.19)$$

The seasonal operation strategy (FSS) is introduced for a CCHP system and is based on a parameter called the Load Ratio (LR), defined as

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$$LR = \frac{Monthly\ Electric\ Load}{Monthly\ Thermal\ Load} \qquad (5.20)$$

For a particular month, if $LR > 1$ the CCHP system operates following the electric load (FEL) and if $LR < 1$ the system operates following the thermal load (FTL).

For constant load operation, the PGU will operate continuously at a constant rate. In this study the minimum electric output of the PGU, E_{min}, and the full load of the PGU, L, were investigated.

CHAPTER 6

CHP-ORC AND CCHP-ORC SYSTEMS

The CHP-ORC system, Figure 6.1, combines a CHP system and an organic Rankine cycle. When the recovered waste heat is more than the required heat, an ORC can use the excess heat to generate electricity. Similarly, an ORC can be combined with a CCHP system.
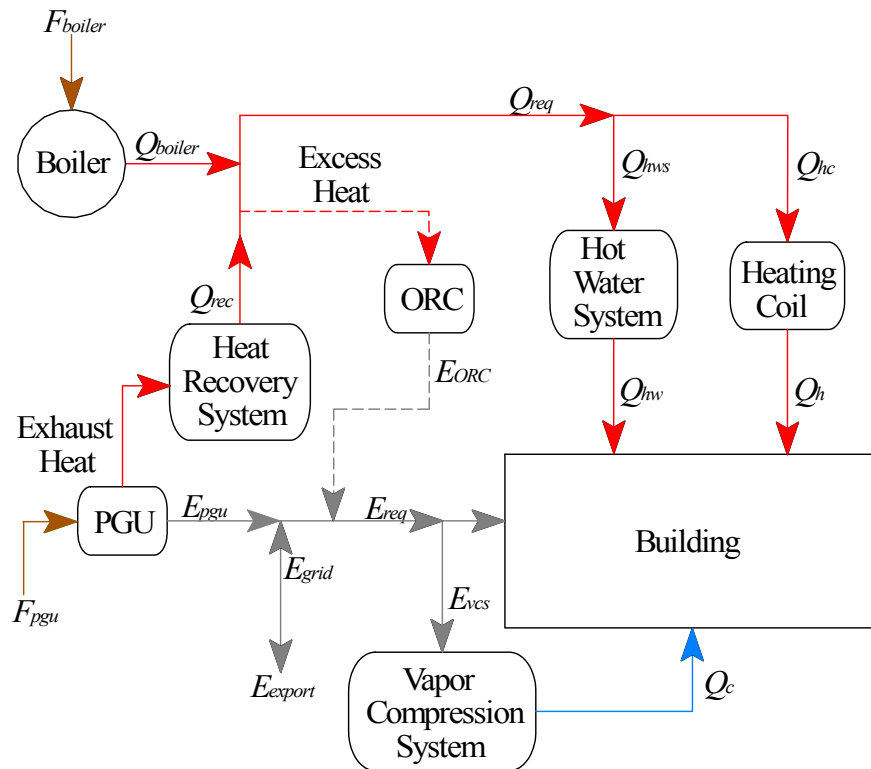
Figure 6.1   CHP-ORC system schematic

Figure 6.2 illustrates the ORC configuration. In the evaporator, waste heat from the CHP system evaporates the working fluid. The vapor then expands through a turbine, which drives a generator to produce electricity. After the turbine, the working fluid enters the condenser where the fluid returns to a liquid that is then pumped back to the evaporator to repeat the cycle.
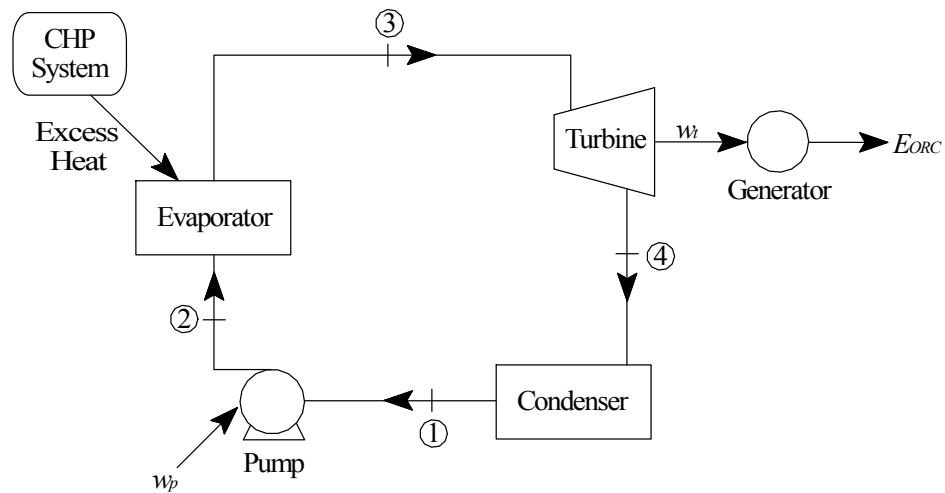
Figure 6.2   ORC system schematic

6.1   CHP-ORC and CCHP-ORC System Model

For the CHP-ORC system, the amount of electricity that must be supplied by the CHP-ORC system and/or the grid is the same as for stand-alone CHP system, Equation (5.1). Also, the heat that must either be recovered from the PGU or supplied by the boiler is the same as for the CHP system, Equation (5.2). Similarly, for the CCHP-ORC system the required electricity and required heat are the same as for the CCHP system, Equation (5.13) and (5.14), respectively.

The amount of thermal energy recovered from the PGU dictates the need for the boiler or the ORC. When the thermal energy recovered from the PGU is higher than the thermal energy needed to handle the thermal load, the ORC can generate electricity by using the excess recovered thermal energy. Therefore, the amount of heat available to the ORC to heat the organic working fluid in the evaporator, Q_e, is

$$Q_e = (Q_{rec} - Q_{req})\varepsilon \quad \text{if } Q_{rec} > Q_{req} \tag{6.1}$$

where ε is the evaporator effectiveness and Q_{rec} was given in Equation (5.9).

For the ORC cycle, values for the evaporator pressure ($P_2 = P_3$) and the condenser pressure ($P_4 = P_1$) are chosen along with isentropic efficiencies for the turbine and pump. In addition, the working fluid is assumed to enter the pump as a saturated liquid ($x_1 = 0$) and exit the evaporator as a saturated vapor ($x_3 = 1$). The latter choice is based on a study by Mago et al. [39] that demonstrated superheating the organic working fluid does not increase the cycle efficiency. From the above information, the efficiency of the ORC system can be determined as outlined.

For process 1 to 2, the specific work input required by the pump, w_p, is

$$w_p = \frac{w_{p,s}}{\eta_p} = \frac{(h_{2,s} - h_1)}{\eta_p} \tag{6.2}$$

where $w_{p,s}$ is the ideal (isentropic) specific work of the pump, η_p is the isentropic efficiency of the pump, h_1 is the enthalpy at the pump inlet of the saturated fluid, and $h_{2,s}$ is the enthalpy of the working fluid at the exit of the pump for the ideal (isentropic) case. The enthalpy at state two, h_2, can be found accordingly as

$$h_2 = w_p + h_1 \tag{6.3}$$

For process 2 to 3, the specific heat transfer required in the evaporator, q_e, is

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$$q_e = h_3 - h_2 \qquad (6.4)$$

where h_3 is the enthaply at the evaporator exit of the saturated vapor. For process 3 to 4, the specific work output from the turbine, w_t is

$$w_t = w_{t,s}\eta_t = (h_3 - h_{4,s})\eta_t \qquad (6.5)$$

where $w_{t,s}$ is the ideal specific work of the turbine, η_t is the turbine isentropic efficiency, and $h_{4,s}$ is the enthalpy of the working fluid at turbine outlet for the ideal (isentropic) case. The efficiency of the ORC system is then

$$\eta_{ORC} = \frac{w_t - w_p}{q_e} \qquad (6.6)$$

While the specific values for work and heat transfer do not change and, therefore, the efficiency remains constant, the mass flow rate of the working fluid will adjust to absorb all of the available heat in the evaporator, such that

$$Q_e = mq_e \qquad (6.7)$$

where m is the mass flow rate of the working fluid over an hour. The net electric energy from the ORC is then

$$E_{ORC} = Q_e\eta_{ORC}\eta_{gen} \qquad (6.8)$$

where η_{gen} is the electric generator efficiency. The electric ouput from the CHP-ORC system (or CCHP-ORC system) is

$$E_{CHP-ORC} = E_{pgu} + E_{ORC} \qquad (6.9)$$

The operational strategy still dictates the electric output of the PGU. The method of determining the fuel consumed by the PGU remains the same as for the standalone system and is determined by Equation (5.5); however, to determine the electricity

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imported and exported from the grid, Equations (5.3) and (5.4), respectively, are modified by replacing E_{pgu} with $E_{CHP\text{-}ORC}$ as follows

$$E_{grid} = \begin{cases} E_{req} - E_{CHP-ORC} & \text{if} & E_{CHP-ORC} < E_{req} \\ 0 & \text{if} & E_{CHP-ORC} \geq E_{req} \end{cases} \tag{6.10}$$

$$E_{export} = \begin{cases} E_{CHP-ORC} - E_{req} & \text{if} & E_{CHP-ORC} > E_{req} \\ 0 & \text{if} & E_{CHP-ORC} \leq E_{req} \end{cases} \tag{6.11}$$

As is the case for the CHP and CCHP systems, if the recovered thermal energy is not enough to handle the total thermal load, the boiler has to provide additional heat. For this case $E_{ORC} = 0$ and Equation (5.10) is used to determine the heat required by the boiler, and Equation (5.11) can be used to determine the fuel consumed in the boiler.

Under the FEL operational strategy, the addition of the ORC will reduce the amount of electricity that the PGU must generate. Assuming there is extra heat available to run the ORC, the electric output of the PGU that results in the CHP-ORC system meeting the required electric load can be determined by combining Equations (5.9), (6.1), (6.8), and (6.9), which results in

$$E_{pgu}^{\circ} = \frac{E_{req} + (Q_{req} - \eta_{rec} * \beta)\varepsilon * \eta_{ORC}\eta_{gen}}{1 + \eta_{rec}(\alpha - 1)\varepsilon * \eta_{ORC}\eta_{gen}} \tag{6.12}$$

where E_{pgu}° is the electric output of the PGU that results in $E_{CHP-ORC} = E_{req}$ (assuming there is extra heat). Therefore, for a FEL strategy, the electric output of the PGU is

$$E_{pgu} = \begin{cases} E_{min} & \text{if} & E_{pgu}^{\circ} < E_{min} \\ E_{pgu}^{\circ} & \text{if} & E_{min} \leq E_{pgu}^{\circ} < L \\ L & \text{if} & L \leq E_{pgu}^{\circ} \end{cases} \quad \text{for } E_{req} > E_{Q_{req}} \tag{6.13a}$$

$$E_{pgu} = \begin{cases} E_{min} & \text{if} & E_{req} < E_{min} \\ E_{req} & \text{if} & E_{min} \leq E_{req} < L \\ L & \text{if} & L \leq E_{req} \end{cases} \quad \text{for } E_{req} \leq E_{Q_{req}} \tag{6.13b}$$

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CHAPTER 7

SYSTEM PERFORMANCE AND OPTIMIZATION

One method used throughout this study to evaluate the performance of CHP systems is to compare the annual operational cost, primary energy consumption (PEC), and carbon dioxide emissions (CDE) to the reference case. In addition, the study of the load-share turbine for the large office considers carbon credits along with capital costs.

7.1 Cost

7.1.1 Operational cost

A common and simple method of computing the operational costs incurred by a CHP system is to use an average price for electricity and natural gases. In this instance, the operational cost is determined according to

$$Cost = \left(E_{grid} - E_{export}\right)p_e + (F_{boiler} + F_{pgu})p_{ng} \qquad (7.1)$$

where p_e and p_{ng} are an average electriciy and natural gas price.

In parts of this study, however, actual price data are used. For natural gas, historical monthly averages from the respective state are employed. This accounts for month-to-month fluctuations in price along with price variations across different locations. The utility rate structures for the individual cities were taken from the EnergyPlus input file for the benchmark model. These utility rates are for a monthly billing cycle and contain base rates, block charges, and/or demand charges all of which

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may be seasonal (i.e., depend on the time of year). Information about selling electricity back to the grid was unavailable, so assumptions were made as to how to price exported electricity. Energy charges make up the base of each monthly utility bill, where the energy charge rate ($/kWh) is multiplied by the electricity consumed from the grid for that month. For exported electricity, the customer would receive half the rate of purchased electricity. Therefore, the energy charges are computed as follows

$$EnergyCharges = E_{grid}r_e - E_{export}0.5r_e \tag{7.2}$$

where r_e is the energy charge rate for electricity (in $/kWh) which may vary depending on the time of year. To calculate the block charges, a net grid consumption of $E_{grid} - 0.5 * E_{export}$ is determined for the month. From this, the first block size of electricity consumed is billed at block 1's cost, the next block size at block 2's cost, the next block size at block 3's cost, and the remaining net grid consumption is billed at the remaining cost. Demand charges are not normally present for small office buildings because of the low electricity consumption and low demand, which is consistent with the cities selected in this study. For the case of the large office in Chicago, demand charges are built into a separate block structure where the block sizes are multiplied by the demand for that month. The monthly subtotal can then be computed according to

$$Subtotal = EnergyCharges + BlockCharges \tag{7.3}$$

and the total monthly cost for electricity is

$$Cost_e = (Subtotal + MonthlyCharge)(1 + t) \tag{7.4}$$

where t is the tax rate which was taken to be 2% above the location's sales tax rate [32] and the monthly charge is a fixed price for connection to the grid.

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The monthly cost of natural gas is

$$Cost_{ng} = \left(F_{pgu} + F_{boiler}\right)(r_{ng})(1 + t) \qquad (7.5)$$

where r_{ng} is the monthly price of natural gas (\$/kWh) and the fuel consumption, $F_{pgu} + F_{boiler}$, is for the given month.

7.1.2 Total cost with carbon offsetting

Offsetting carbon dioxide emissions through the purchase of carbon credits adds to the yearly operational costs, *Cost*, which is the summation of the monthly electricity cost and the monthly natural gas cost for each month of the year. Therefore, the total cost including carbon offsetting is

$$Cost_{total} = Cost + CDE * CC \qquad (7.6)$$

where *CC* is the carbon credit value in \$/metric ton of CO_2-equivalent and *CDE* are the annual carbon dioxide emissions.

7.1.3 Capital Costs

When compared to the reference case, the total operational savings from a CHP system are

$$Savings_{CHP} = Cost_{ref} - Cost_{CHP} \qquad (7.7)$$

where the costs can include carbon offsetting. While installing a CHP system can provide savings in terms of reduced operational costs, there are normally higher capital costs associated with the implementation of such a system. When deciding whether or not to invest in a CHP system this tradeoff must be weighed, and one such method is to evaluate the simple payback period. The simple payback period estimates the number of years of operation needed before the initial investment can be recouped. Although, this

method does not consider the time value of money or account for factors such as capital depreciation. For many businesses, the maximum payback period for any investment is set. In this situation, the maximum allowable increase in capital cost over the reference case can be determined from the set payback period. This can be expressed as

$$\Delta_{cost} = CapitalCost_{CHP} - CapitalCost_{ref} = Payback * Savings_{CHP} \qquad (7.8)$$

Therefore, to guarantee this payback period, the above equation can be used to estimate the total investment available to upgrade to a CHP system or the extra investment over the reference case's capital costs that can be made to install a CHP system in a new building.

7.2   PEC and CDE

Primary energy (sometimes called source energy) consumption is the raw fuel required to operate the building. It includes site energy, the amount of energy measured by the meter, plus losses incured from production, transmission, delivery, etc. Primary energy allows comparison among buildings that use different sources of energy and better reflects the building's resource consumption. For the office buildings, there are two metered energy sources: grid electricity and fuel. To determine primary energy consumption, PEC conversion factors, unique to a type of metered energy source, are multiplied by the amount of that energy that is consumed on site. For example, the electricity conversion factor converts the site electricity consumed from the grid to the fuel used by the power plant. The natural gas conversion factor accounts for the energy required to extract, process, and deliver the fuel. Given this, the PEC of the building operating the CHP system is calculated in the following manner

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$$PEC = (E_{grid} - E_{export})CF_{PEC,e} + (F_{pgu} + F_{boiler})CF_{PEC,ng} \qquad (7.9)$$

where $CF_{PEC,e}$ and $CF_{PEC,ng}$ are the primary energy conversion factors for electricity and natural gas. Similarly, to determine carbon dioxide emissions, CDE conversion factors are used.

$$CDE = (E_{grid} - E_{export})CF_{CDE,e} + (F_{pgu} + F_{boiler})CF_{CDE,ng} \qquad (7.10)$$

where $CF_{CDE,e}$ and $CF_{CDE,ng}$ are the emission conversion factors for delivered electricity and natural gas. The emission conversion factor for natural gas includes processing and delivery of the fuel along with the on-site combustion of the fuel. In computing PEC and CDE, the net electricity imported from the grid is used. This is because exported electricity displaces electricity that must otherwise be generated by the power plant to serve its customers, thereby reducing the amount of raw fuel consumed.

To determine the distribution of CDE by source, the total carbon dioxide emissions can be broken down accordingly

$$CDE = CDE_{electricity} + CDE_{fuel-pre} + CDE_{fuel-pgu} + CDE_{fuel-boiler} \qquad (7.11)$$

where $CDE_{electricity}$ are the carbon dioxide emissions for delivered electricity, $CDE_{fuel-pre}$ are the precombustion carbon dioxide emissions for fuel, and $CDE_{fuel-pgu}$ and $CDE_{fuel-boiler}$ are, respectively, the PGU and boiler on-site carbon dioxide emissions resulting from fuel combustion. The carbon dioxide emissions for delivered electricity can be expressed as

$$CDE_{electricity} = (E_{grid} - E_{export})CF_{CDE,e} \qquad (7.12)$$

The precombustion carbon dioxide emissions for fuel delivery to the building and the on-site carbon dioxide emissions from combustion in the PGU and boiler can be determined, respectively, as

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$$CDE_{fuel-pre} = (F_{pgu} + F_{boiler})CF_{CDE,ng-pre} \tag{7.13}$$

$$CDE_{fuel-pgu} = (F_{pgu} + F_{boiler})CF_{CDE,ng-pgu} \tag{7.14}$$

$$CDE_{fuel-boiler} = (F_{pgu} + F_{boiler})CF_{CDE,ng-boiler} \tag{7.15}$$

where $CF_{CDE,ng-pre}$, $CF_{CDE,ng-pgu}$, and $CF_{CDE,ng-boiler}$ are the emission conversion factors for precombustion (extraction, processing, and delivery of natural gas), PGU on-site combustion, and boiler on-site combustion, respectively.

7.3   Optimization

Simple optimizations of a CHP system can be done to minimize one of the following three criteria: operational cost, primary energy consumption, or carbon dioxide emissions. To determine the hourly electrical output of the PGU that minimizes the hourly PEC, Equations (5.3) through (5.5) and Equations (5.9) through (5.11) were inserted into the equation for PEC, Equation (7.1), which results in

$$PEC = max[E_{req} - E_{pgu}, E_{pgu} - E_{req}]CF_{PEC,e}$$
$$+ \left[\alpha * E_{pgu} + \beta + \frac{max[Q_{req} - \eta_{rec}(\alpha * E_{pgu} + \beta - E_{pgu}),0]}{\eta_{boiler}}\right]CF_{PEC,ng} \tag{7.16}$$

This expression for PEC is a linear piecewise function of E_{pgu}. Therefore, the minimum primary energy that a CHP system will consume occurs at either an endpoint of the function or a point of discontinuity. The two endpoints are $E_{pgu} = E_{min}$ and $E_{pgu} = L$, while discontinuities occur at $E_{pgu} = E_{req}$ (FEL) and $E_{pgu} = E_{Q_{req}}$(FTL). An alternative would be to turn the CHP system off and solely rely on the grid and boiler. When the CHP system is off, electricity from the grid will meet the building's electric demand and the boiler is responsible for the building's heat-driven thermal loads. For the CCHP

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system, this means the boiler is responsible for the cooling load through the absorption chiller, unlike the reference case relies on eletricity to produce the needed cooling. For each hour of the optimized simulation, the PEC value for the engine running at E_{min}, L, FEL, FTL, and turned off was determined. The option providing the lowest PEC value was chosen as the PGU load for that hour. Note, the PEC function, Equation (7.16) changes each hour since the values for the hourly electricity and heat required by the building, E_{req} and Q_{req}, respectively, change.

For CDE minimization, CDE conversion factors replace the PEC conversion factors in Equation (7.16) and the process is repeated. Minimizing operational costs is slightly more complicated due to the cost structure and the different treatment of imported and exported electricity. Under this optimization strategy, the PGU is operated to minimize the marginal cost for each hour, which is calculated according to

$$Cost_{hour} = E_{grid} * mr_e - E_{export} * 0.5mr_e + (F_{pgu} + F_{boiler})(mr_{ng}) \quad (7.17)$$

where *mr* denotes a marginal rate, which depends on the month, tax rate, and, in the case of block charges, the amount of electricity already consumped during the month. Substituting Equations (5.3) through (5.5) and Equations (5.9) through (5.11) into (5.17) gives

$$Cost_{hour} = max(E_{req} - E_{pgu}, 0)mr_e - max(E_{pgu} - E_{req}, 0) * 0.5mr_e$$
$$+(\alpha * E_{pgu} + \beta)mr_{ng} \quad (7.18)$$
$$+ \left[\frac{max[Q_{req} - \eta_{rec}(\alpha * E_{pgu} + \beta - E_{pgu}),0]}{\eta_{boiler}}\right] mr_{ng}$$

The same endpoints and discontinuities are present as for optimizing PEC and CDE. So, for each hour of the optimized simulation the marginal costs of the PGU operating at

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E_{min}, L, FTL, FEL, and turned off are determined. The option providing the lowest cost was chosen as the PGU load. Optimizing the system allows the system to turn off when it is beneficial to do so, unlike the FEL, FTL, and constant load (E_{min} and L) operational strategies presented in Section 5.3, which require the PGU to operate continuously.

During some simulations FEL was the only modeled strategy, so optimization of theses system consisted of comparing the system operating to follow the electric load against turning the engine off.

7.4   CCHP System and CCHP Building Efficiency

For certain cases that optimized the CCHP system, the efficiency of the CCHP system and the overall building efficiency were also determined. The efficiency of the CCHP system is

$$\eta_{CCHP} = \frac{Q_h + Q_{ch} + Q_{hw} + E_{pgu}}{F_{boiler} + F_{pgu}} \tag{7.19}$$

and the overall efficiency of the building based on primary energy, η_B, is calculated, respectively, according to

$$\eta_B = \frac{Q_h + Q_{ch} + Q_{hw} + E_{pgu} + E_{grid}}{E_{grid} * CF_{PEC,e} + (F_{boiler} + F_{pgu}) * CF_{PEC,ng}} \tag{7.20}$$

Similarly, the overall efficiency based on primary energy for the reference building is

$$\eta_{REF} = \frac{Q_h + Q_{hw} + E_{grid}}{E_{grid} * CF_{PEC,e} + F_{boiler} * CF_{PEC,ng}} \tag{7.21}$$

The next four chapters, Chapters 8-11, are the individual investigations that were outlined at the end of Chapter 2:

8. A review of the economical, energy, and environmental benefits of CHP and CHP-ORC systems

9. Influence of prime mover size and operational strategy on the performance of CCHP and CHP systems under different cost structures

10. Analysis and optimization of a CCHP-ORC system and a CHP-ORC system for a small commercial office building

11. Evaluation of a turbine driven CCHP system for a large office building under different operating strategies

Within each chapter results are given along with discussion. A majority of the results are presented as the percent variation with respect to the reference case. For example, the CDE performance of the CHP system with respect to the reference building can be computed using

$$\%Variation = \frac{CDE_{ref} - CDE_{CHP}}{CDE_{ref}} * 100\% \qquad (7.22)$$

Therefore, a negative number signifies a reduction from the reference case while a positive number indicates an increase from the reference case.

CHAPTER 8

A REVIEW OF THE ECONOMICAL, ENERGY, AND ENVIRONMENTAL

BENEFITS OF CHP AND CHP-ORC SYSTEMS

This section evaluates the energy, economical, and environmental benefits of a
CHP system and a CHP-ORC system for a small commercial office building in different
North American climates. An investigation into the benefits of CHP systems based on
the Energy Star program and the LEED program is included in this section. In addition,
the ability of the CHP-ORC system to reduce the amount of electricity generated by the
PGU of the CHP system and the subsequent effect on the total fuel consumption are
evaluated. The U.S. climate zones map from ASHRAE Standard 90.1, illustrated in
Figure 8.1 [40], served as the basis for choosing the locations to study. Table 8.1 gives
the chosen cities and their respective climate zone for the CHP and CHP-ORC system
analyses. In some North American cities, and especially for a small office building,
exporting electricity is unavailable, thus, any electricity surplus would go unused.
During this investigation, the option to export electricity was not available and the CHP
and CHP-ORC systems were operated according to follow the electric load with cutoff,
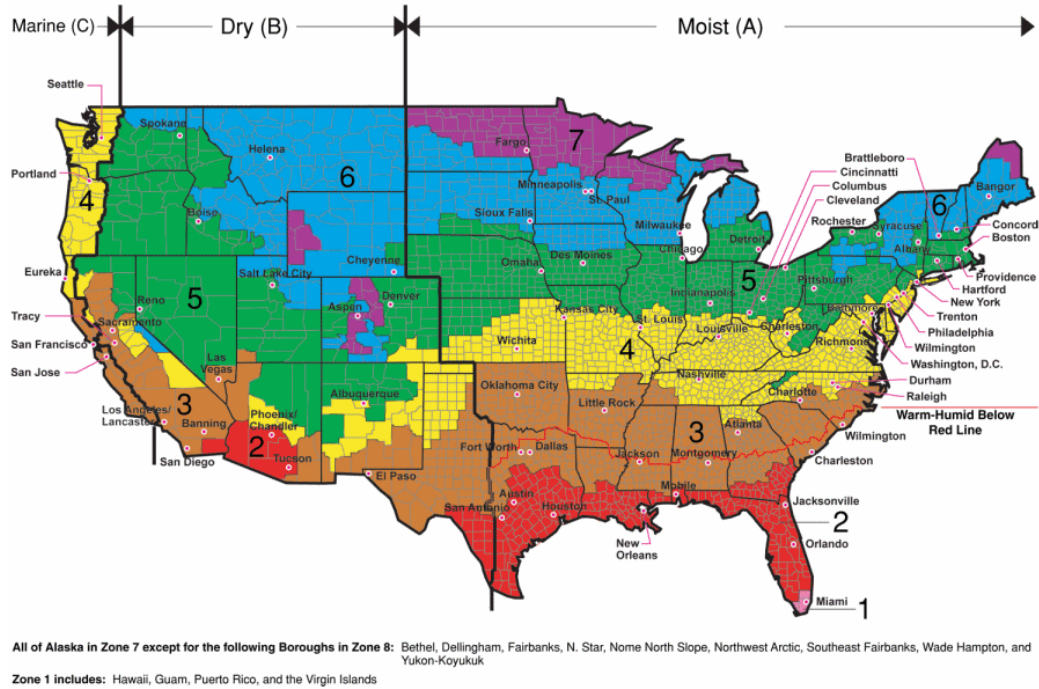Equation (5.16), in order to avoid wasted electricity.

Figure 8.1   U.S. climate zones from ASHRAE Standard 90.1-2007 [40]

Table 8.1   Selected locations for the CHP and CHP-ORC systems

CHP Analysis	CHP-ORC Analysis	Climate Zone
Miami, FL	Miami, FL	1A
Houston, TX	Houston, TX	2A
Atlanta, GA	Atlanta, GA	3A
Los Angeles, CA	Los Angeles, CA	3B
Seattle, WA		4C
Boulder, CO		5B
Helena, MT		6B
Duluth, MN	Duluth, MN	7
Fairbanks, AK	Fairbanks, AK	8

The primary energy conversion factors used in this investigation, listed in Table 8.2, are national averages. Because primary energy is the basis for calculating the Energy Star rating and the aim of the Energy Star rating system is to rank building energy performance relative to its peers, the U.S. Environmental Protection Agency (EPA) [28]

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has determined that it is most equitable to employ national-level primary energy conversion factors. The use of national primary energy conversion factor ensures that no specific building will be credited or penalized for the relative efficiency of its utility provider. Therefore, there is only one primary energy conversion factor for each type of metered energy. On the other hand, the emission conversion factors, given in Table 8.3, do not affect the Energy Star rating and are different for each region. The emission conversion factors for electricity depend on the mix of fuel sources used to generate electricity in each specific region. Table 8.3 also lists the prices used for electricity and natural gas, which are national averages.

Table 8.2   Primary energy conversion factors [29]

Fuel Type	CF_{PEC}* (kWh/kWh)
Electricity	3.339
Natural gas	1.047

* Values obtained in March 2009

Table 8.3   CDE conversion factors and prices for electricity and natural gas [29]

Representative City	$CF_{CDE,e}$* (tons/kWh)	$CF_{CDE,ng}$* (tons/kWh)	r_e* ($/kWh)	r_{ng}* ($/MBtu)
Miami, FL	0.000601	0.0002	0.097	13.65
Houston, TX	0.000603	0.0002	0.100	10.04
Atlanta, GA	0.000601	0.0002	0.097	13.65
Los Angeles, CA	0.000330	0.0002	0.130	10.17
Seattle, WA	0.000412	0.0002	0.065	11.44
Boulder, CO	0.000858	0.0002	0.076	9.55
Helena, MT	0.000412	0.0002	0.080	11.35
Duluth, MN	0.000831	0.0002	0.074	9.98
Fairbanks, AK	0.000560	0.0002	0.119	4.49

* Values obtained in March 2009

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Table 8.4 gives the values of the variables used to simulate the CHP system. Table 8.5 gives the parameters of the ORC cycle for the CHP-ORC system. For the analysis, R113, which is a dry fluid, was selected as the working fluid since it has been proven to be a good candidate for ORC applications [12],[27]. One of the reasons dry fluids exhibit better thermal efficiencies over wet fluids is that they do not they do not need to be superheated since the fluid does not condense after it goes through the turbine.

Table 8.4   Input values for CHP system simulation

Variable	Value
Heat recovery system efficiency, η_{rec}	0.8
CHP boiler efficiency, η_{boiler}	0.8
Heating coil efficiency, η_{hc}	0.8
PGU rated load, L (kW)	18
PGU coefficient*, α	2.70288
PGU coefficient*, β	22.42087

*Kohler residential generator sets [41]

Table 8.5   ORC input values for CHP-ORC system simulation

Variable	Value
Organic working fluid	R113
Evaporator pressure (MPa)	3
Evaporator exit quality	1
Condenser temperature (°C)	25
Turbine efficiency (%)	82
Pump efficiency (%)	80
Generator efficiency (%)	85
Resulting ORC efficiency, η_{ORC} (%)	19.9

Using the model described in Section 5.1 for a CHP system combined with a vapor compression system for cooling and the model outlined in Section 6.1 for a CHP-ORC system, the annual PEC, cost, and CDE for the selected locations were determined.

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Small office buildings usually only operate 11 or 12 hours a day, and not 24 hours a day. Therefore, the CHP and CHP-ORC systems were also simulated to operate between typical office hours, 7:00 am to 7:00 pm. At night when the system is off, the grid and boiler meet the building loads. For the CHP system, a simple optimization was done comparing the FELc strategy to turning the engine off and relying on the grid and boiler. The impact of the CHP system on the Energy Star rating and LEED program is reviewed and the ability of the CHP-ORC system to reduce the total fuel consumption is evaluated.

8.1   Cost, PEC, and CDE Results for the CHP System

For the cities evaluated in this investigation, Figure 8.2 presents the variation with respect to the reference case of the cost, PEC, and CDE for the CHP system operating according to FELc for 24 hours a day. This figure illustrates that, in general, if the CHP system operates 24 hours a day the cost, PEC, and CDE increase with respect to the reference case. An exception is a decrease in cost (40%) for Fairbanks, AK due to the low cost of natural gas and high cost of electricity in this region. Therefore, replacing grid electricity with on-site generated electricity from natural gas combustion significantly decreases the cost for this city.

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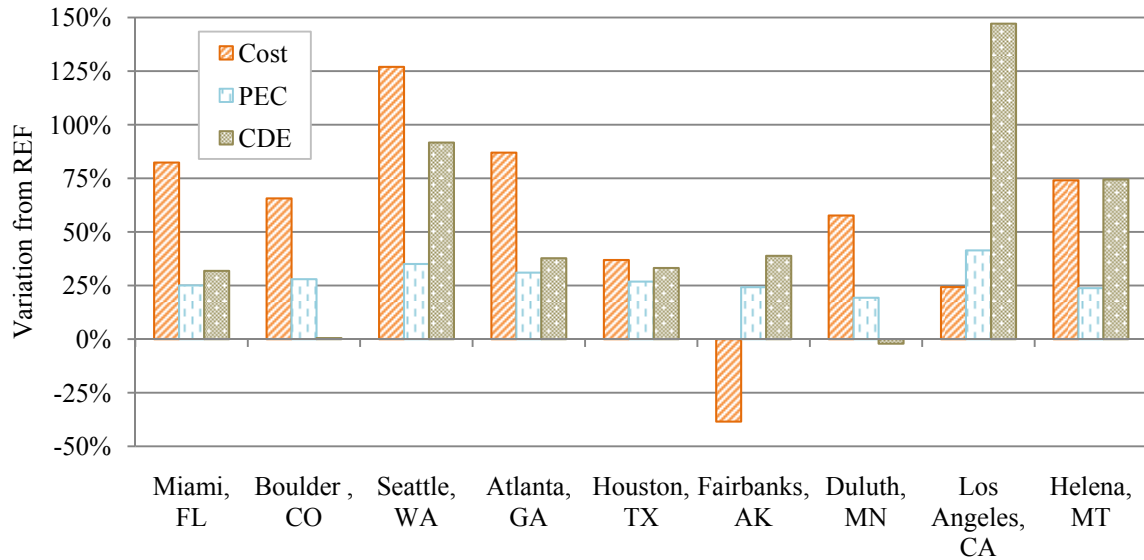
Figure 8.2   Variation from the reference case of the cost, PEC, and CDE for the CHP system operating 24 hours a day

Figure 8.3 illustrates the variation from the reference case of the cost, PEC, and CDE for the CHP system operating from 7:00 am to 7:00 pm for each selected city. Operating the CHP system from 7:00 am to 7:00 pm reduces the operational cost from the reference building's cost for Fairbanks, Los Angeles, and Houston by 47%, 18%, and 12%, respectively.   These cities have the highest rates of electricity; therefore, substituting grid electricity with natural-gas-generated electricity is beneficial.   Even though the cost for the other cities is higher than the reference case cost, they are much lower than the operational cost obtained when the CHP system is operated 24-hours a day (Figure 8.2).   Operating the CHP system for 12 hours a day reduces the PEC for all the evaluated cities.   The highest reduction was obtained for Miami and Duluth (19%) while the lowest reduction was obtained for Los Angeles (11%).   Regarding CDE, operating the CHP system from 7:00 am to 7:00 pm, reduces the CDE below the reference case for all

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the cities except for Seattle, Los Angeles, and Helena. These three cities present the lowest electricity emission conversion factors of the evaluated cities; therefore, substituting natural gas in place of grid electricity will increase the carbon dioxide emissions.
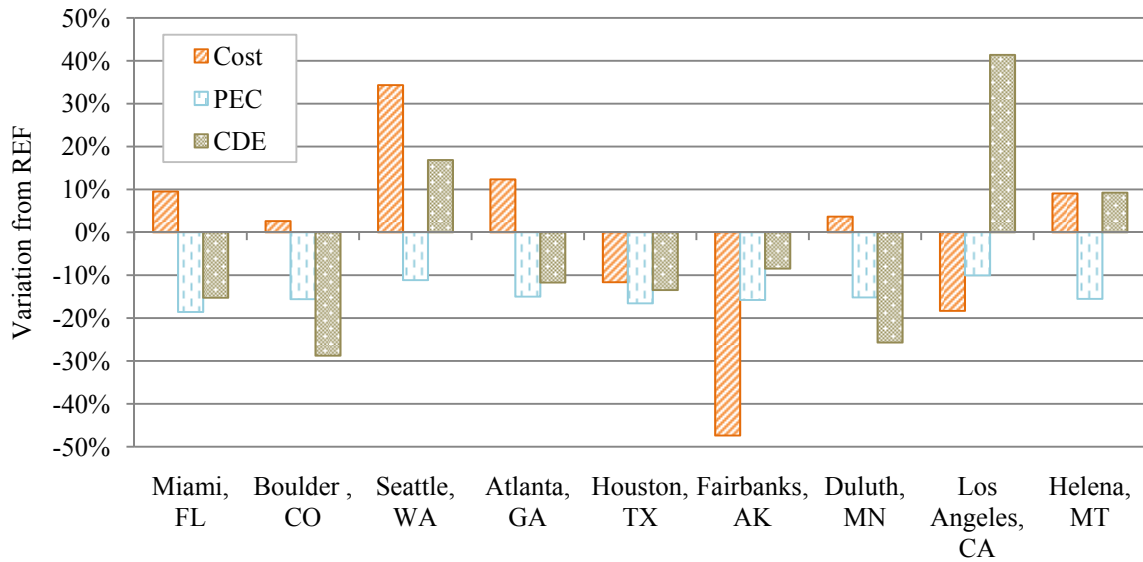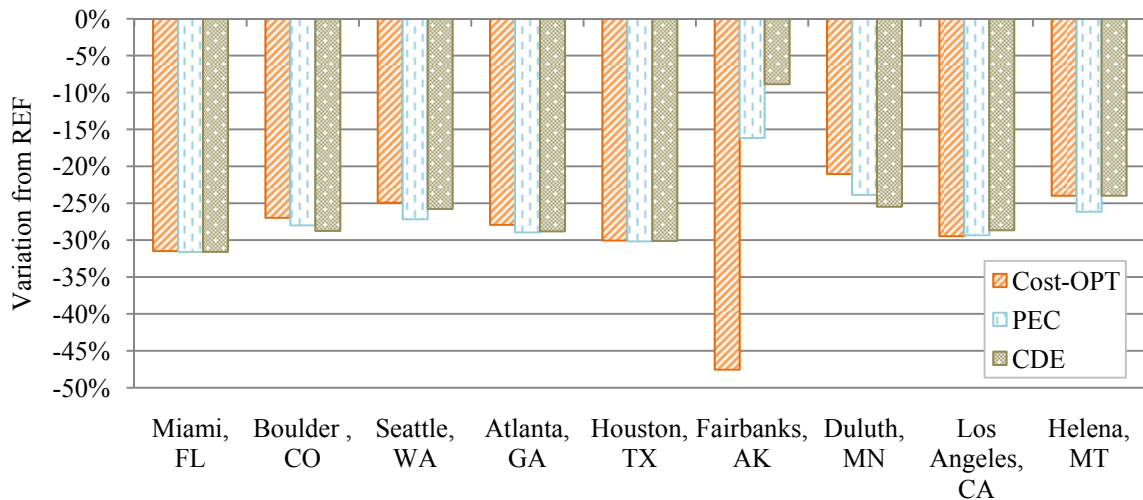

Figure 8.3   Variation from the reference case of the cost, PEC, and CDE for the CHP system operating during office hours from 7:00 am to 7:00 pm

Comparing Figure 8.3 and Figure 8.2 reveals that operating the CHP system during business hours, as opposed to continuously, provides greater benefits. During the winter months, the electric load at night is low causing the PGU to run at low efficiencies. In addition, the low electric load generally means the heat recovered from the PGU is not enough to meet the high heating demand in the winter months, which causes the boiler to consume natural gas in order to fulfill the heating load. In the summer months, the electricity requirement at night is high in order to run the vapor compression system; but the lack of heating demand during the night means there is no

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use for the exhaust heat, which results in low system efficiencies. Therefore, during the night, importing electricity from the grid and buying natural gas as needed is generally cheaper than operating the CHP system at very low efficiencies.

In order to improve the results presented in Figure 8.3 (CHP system operating between 7:00 am and 7:00 pm), operation of the CHP system was optimized based on cost, primary energy consumption, and carbon dioxide emissions. Figure 8.4 displays the results obtained from the cost optimization of the CHP system. Cost optimization reduces the operational cost below that of the reference case for all the cities. The highest cost reduction occurs in Fairbanks (48%) while the lowest reduction happens for Duluth (22%). Optimizing the operational cost also decreases the PEC and CDE with respect to the reference case for all the evaluated cities.
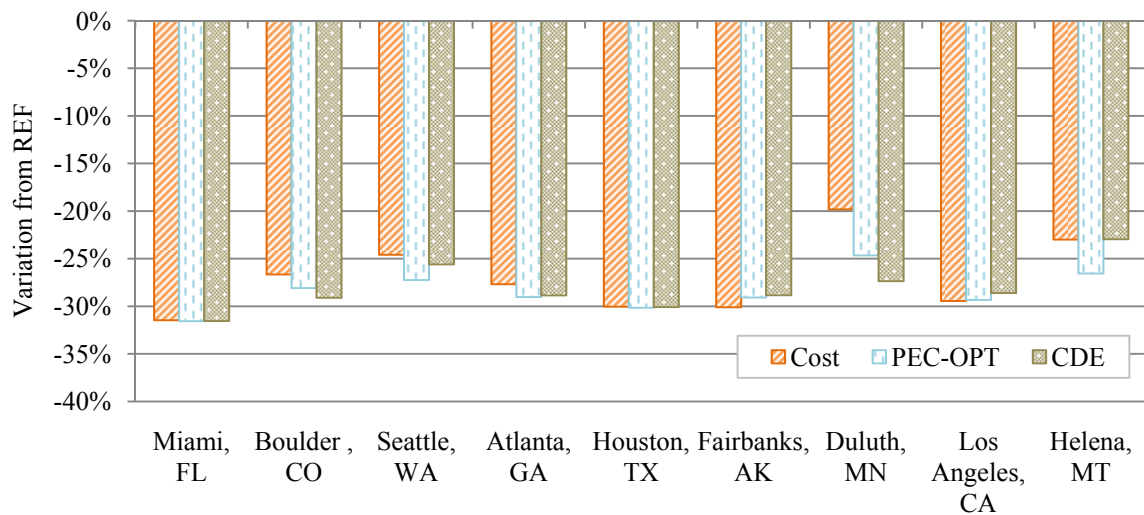

Figure 8.4   Variation from the reference case of the cost, PEC, and CDE for the CHP system operating during office hours from 7:00 am to 7:00 pm optimized for operational cost

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Figure 8.5 illustrates the variation of the cost, PEC, and CDE when PEC is minimized, for which the cost, PEC, and CDE are reduced for all the cities. The highest PEC reduction from the reference case was present in Miami (31%) while the lowest reduction was for Duluth (26%). With the major exception of Fairbanks, optimizing PEC produces similar results to optimizing cost (Figure 8.4). Due to the low price of natural gas and high price of electricity in Fairbanks, there is a tradeoff between PEC and cost, which also exists between CDE and cost.

Figure 8.5   Variation from the reference case of the cost, PEC, and CDE for the CHP system operating during office hours from 7:00 am to 7:00 pm optimized for PEC

The results obtained when the CHP system was optimized based on carbon dioxide emissions are presented in Figure 8.6. This optimization technique also provides good results since it reduces cost, PEC, and CDE for all the evaluated cities. With the exception of Boulder and Duluth, CDE optimization yielded similar results to the PEC optimization of Figure 8.5. In these two cities, CDE optimization provided slightly lower

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emissions than for the PEC optimization, but the accompanying cost is much higher. Therefore, optimizing the CHP system based on cost or primary energy savings was more effective for these locations. However, optimization of the system should be based on the needs of the facility and the location.
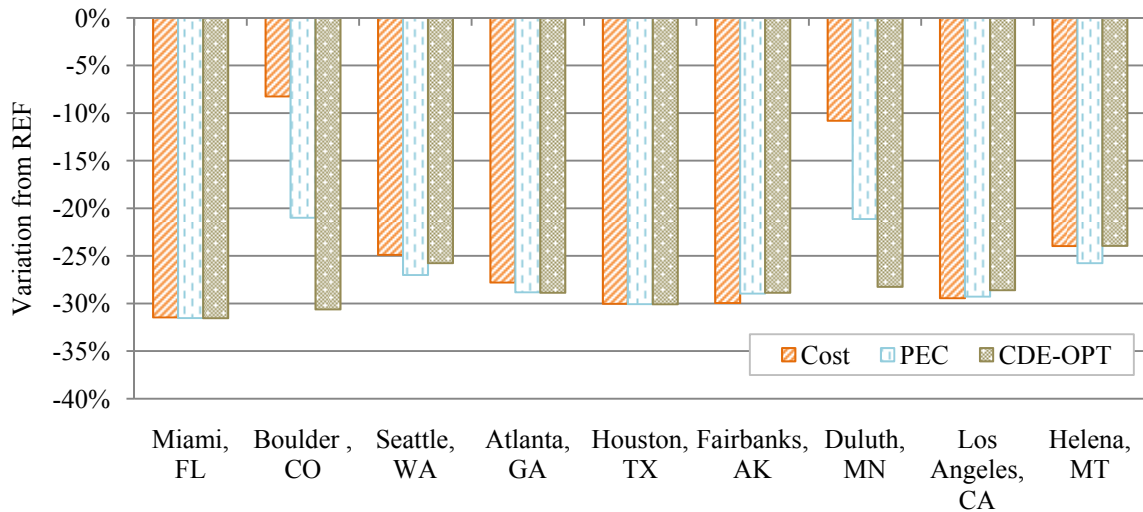

Figure 8.6   Variation from the reference case of the cost, PEC, and CDE for the CHP system operating during office hours from 7:00 am to 7:00 pm optimized for CDE

8.2   Energy Star and LEED Benefits of the CHP System

In addition to reducing cost, PEC, and CDE, CHP systems can offer other benefits. As described in Section 3.1, one such benefit is that the use of a CHP system may help to increase the building's Energy Star rating. Figure 8.7 illustrates the Energy Star rating for the reference case, the building using a CHP system during office hours (from 7:00 am to 7:00 pm) and for the same CHP system operating during office hours but optimized based on minimizing primary energy consumption. The use of the CHP system from 7:00 am to 7:00 pm increases the Energy Star rating when compared to the

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reference case for all the evaluated cities. For all the cities except Miami, Houston, and Duluth, the rating rises above 75, which makes them eligible to receive the Energy Star label. Furthermore, the optimized CHP system (based on primary energy reduction) raises the Energy Star rating over the non-optimized CHP system for all the evaluated cities. Under this operation mode, the cities of Miami, Houston, and Duluth exceed 75, making these three cities eligible to receive the Energy Star label.
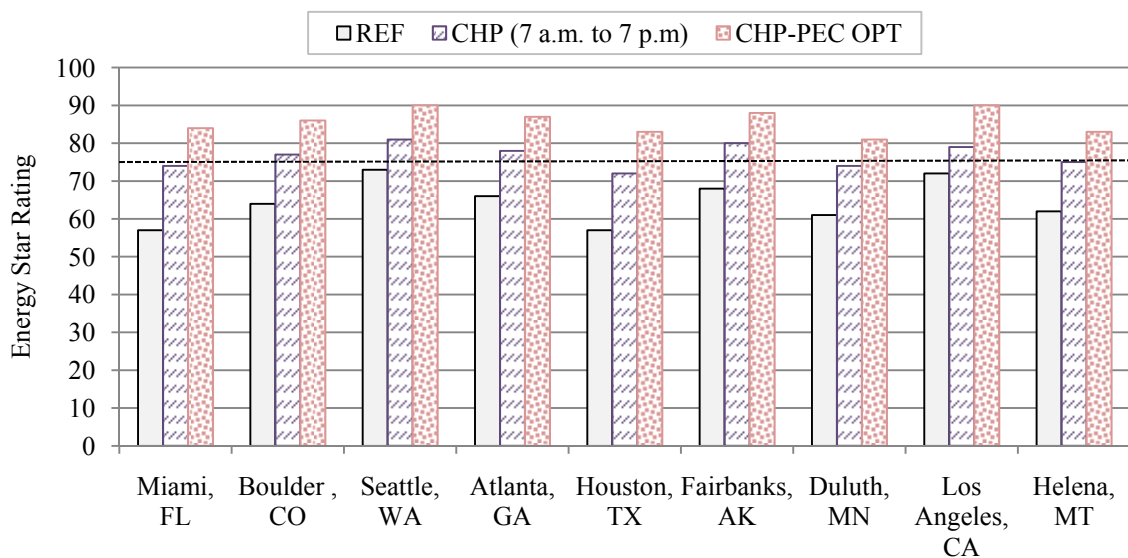

Figure 8.7   Energy Star rating for the conventional building and for the CHP building operating from 7:00 am to 7:00 pm with and without PEC optimization

Section 3.1 also explained how the use of the CHP system could help a building obtain LEED-EB certification by gaining points from an Energy Star rating greater than 70. Figure 8.8 highlights the available LEED-EB points due to the building's Energy Star rating. This figure illustrates that while most cities such as Miami, Boulder, Atlanta, Houston, Duluth, and Helena were not previously eligible for any LEED-EB points, they

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can now achieve LEED-EB points when the CHP system is used. For each city, the optimized CHP system yields the largest number of points and the cities that can acquire the most LEED-EB points are Los Angeles and Seattle with 19. This is almost half of the total number of points needed for LEED-EB certification.
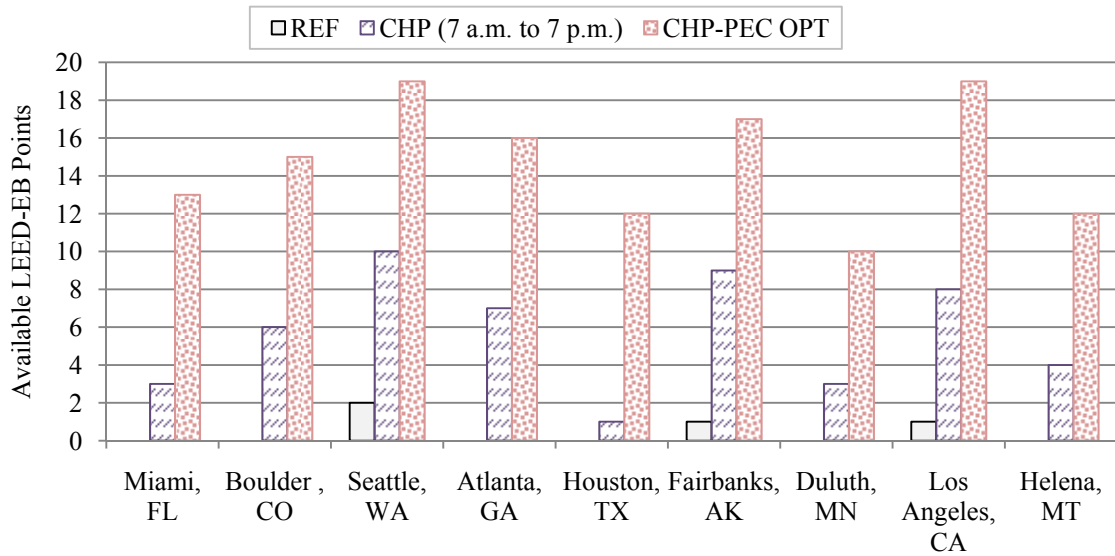

Figure 8.8   Available LEED-EB points from the energy star rating for the conventional building and for the CHP building operating from 7:00 am to 7:00 pm with and without PEC optimization

8.3   Cost, PEC, and CDE Results for the CHP-ORC System

Initially, the CHP-ORC system was operated under FELc throughout the day. For this operation, Figure 8.9 presents the variation of the cost, PEC, and CDE for the CHP-ORC system with respect to the reference case. Results of a CHP system are presented as well for comparison purposes. The use of the CHP-ORC system in Fairbanks and Los Angeles reduces costs by 51% and 11%, respectively, from the reference case. Although the cost to operate the CHP-ORC system remains higher than the reference case for the

remaining cities, the cost is always lower than that obtained to operate the CHP system. Operation of the CHP-ORC system reduces the PEC for all the evaluated cities, while the CHP system increases the PEC between 19% (Duluth) and 41% (Los Angeles). The maximum reduction in PEC for the CHP-ORC system operation was obtained for Duluth, 13.3%. Implementing the CHP-ORC system helps to reduce the CDE for all the evaluated cities from the levels obtained by operating the CHP system alone. The cities of Houston, Duluth, Atlanta, and Miami provide a reduction of CDE with respect to the reference case. Although Fairbanks and Los Angeles produce more CDE than the reference case, it is significantly reduced when compared with the CDE obtained during CHP operation. For the city of Los Angeles, the CDE produced by the CHP systems is almost 150% greater than the reference case. This is due to the low emission conversion factor for this city. Therefore, replacing electricity from the grid with electricity generated by natural gas is not beneficial. These results highlight that, for all the evaluated cities, the use of a CHP-ORC system reduces the cost, PEC, and CDE for the same building operating solely with a CHP system. The average cost, PEC, and CDE reductions are 25.9%, 26.1%, and 26.5%, respectively. However, according to the result presented in Figure 8.9, the system is generally not beneficial when compared to the reference benchmark building.
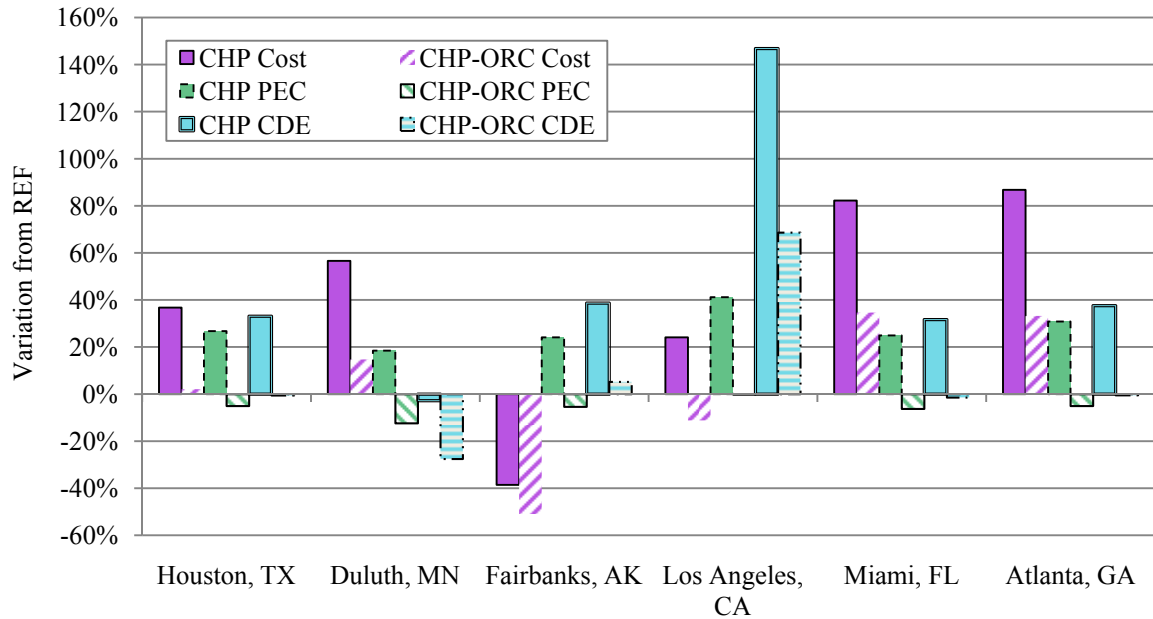
Figure 8.9   Variation from the reference case of the cost, PEC, and CDE for the CHP and CHP-ORC systems operating 24 hours a day

For operation during typical office hours (7 am to 7 pm), Figure 8.10 illustrates the variation of the cost, PEC, and CDE for the CHP-ORC and CHP systems with respect to the reference case. In general, by comparing Figure 8.9 and Figure 8.10, operating during business hours, as opposed to continuously, provides greater benefits for both systems. While the CHP system reduces the operational cost for the cities of Houston, Duluth, Fairbanks, and Los Angeles, the CHP-ORC reduces the cost for all the evaluated cities, and when compared to the CHP system, the CHP-ORC operational cost is reduced by an average 19%. Operating both systems for 12 hours a day reduces the PEC for all the evaluated cities, but the CHP-ORC PEC is lower than the consumption resulting from the CHP system's operation by an average of 19%. The highest PEC reduction for the CHP-ORC system was obtained for the city of Miami (34.4%) while the lowest reduction

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was obtained for Duluth (28.5%). Regarding the CDE, with the exception of Los Angeles, operating the CHP-ORC system from 7:00 am to 7:00 pm, reduces the CDE for all the cities and again yields better results than the CHP system by an average of 20%. In Los Angeles the CDE increased from the reference case by only 3.8%, but when compared to the CHP system the CDE was reduced by 26%. As was the case for the CHP system, operating the CHP-ORC system during office hours improves the performance of the system when compared to operating the CHP-ORC for the whole day.
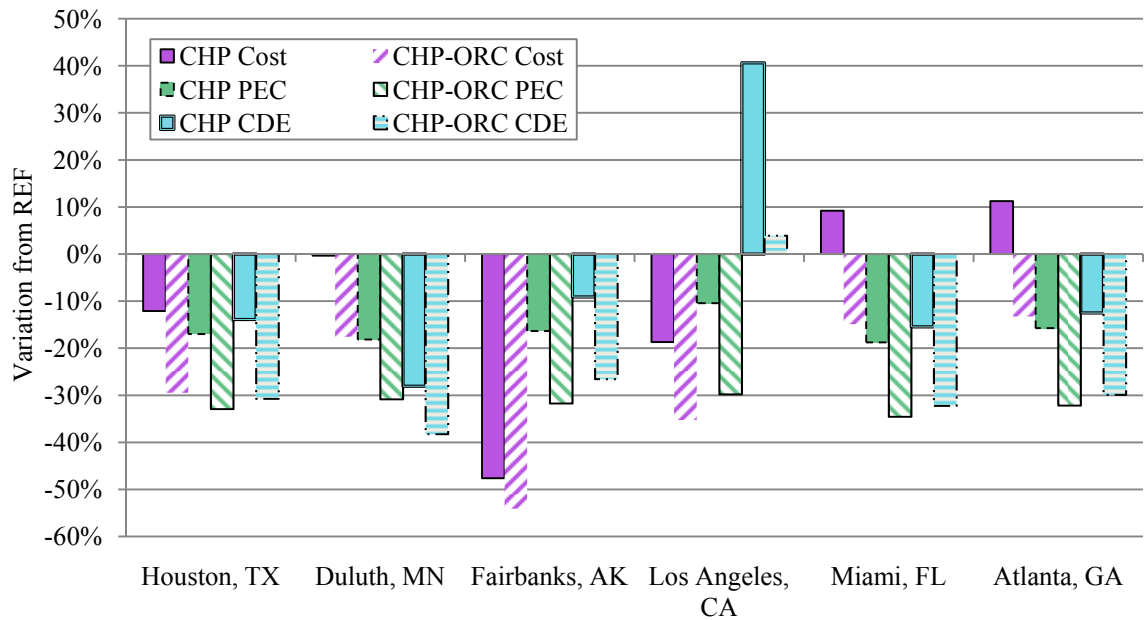
Figure 8.10   Variation of the cost, PEC, and CDE for the CHP and CHP-ORC systems operating 12 hours a day (7:00 am to 7:00 pm)

8.4   CHP-ORC Effect on Fuel Consumption

Figure 8.11 presents a comparison of the fuel energy consumption for the CHP and CHP-ORC systems operating continuously (24 hours a day) and during office hours (12 hours a day). This figure illustrates that the CHP-ORC operation consumes less fuel

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than the CHP operation. For both cases, 24 hours and 12 hours operation, the maximum

reduction was achieved for Los Angeles, 34.7% and 33.5%, respectively. For 24 hours,

the minimum reduction was obtained for Fairbanks, 27%, while the minimum reduction

for 12 hours operation was obtained for Duluth, 22.8%. The average fuel consumption

reduction for the 24 hours and 12 hours operation were 29.9% and 28.3%, respectively.

These results demonstrate the benefits to using an ORC together with a CHP system since

it helps reduce the amount of fuel needed by the PGU of the CHP system while still

satisfying the electric and thermal demand of the building.
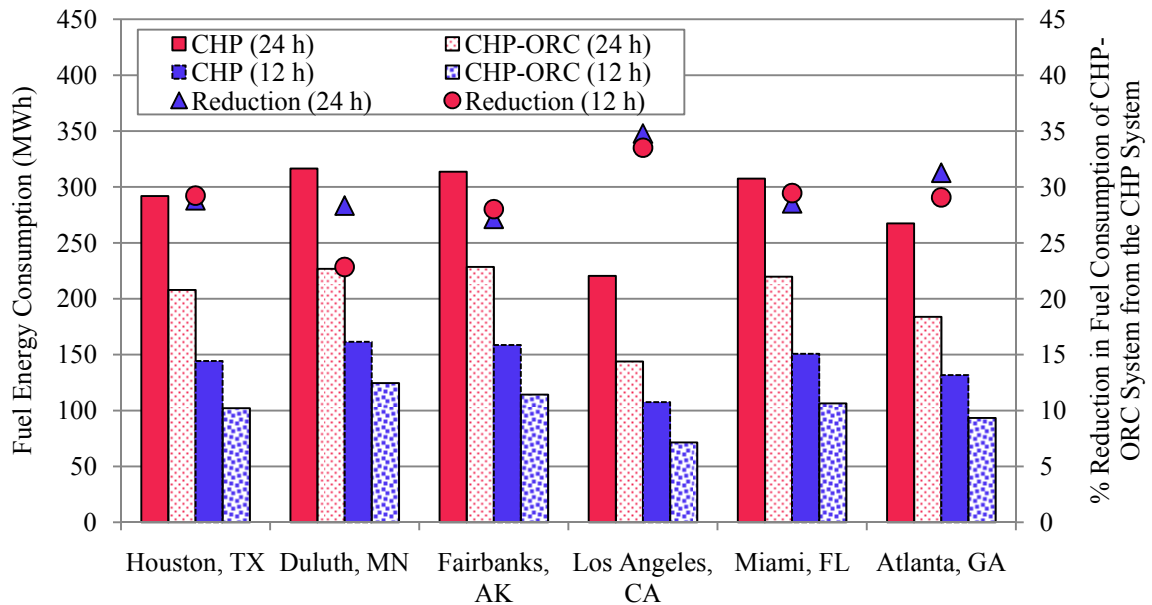
Figure 8.11   Fuel energy consumption during the operation of the CHP and CHP-ORC systems

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CHAPTER 9

INFLUENCE OF PRIME MOVER SIZE AND OPERATIONAL STRATEGY ON THE
PERFORMANCE OF CCHP AND CHP SYSTEMS UNDER DIFFERENT COST
STRUCTURES

For the small office building, the CCHP and CHP systems were first simulated
while operating under the following continuous strategies: E_{min}, FEL, FTL, and L, which
were described in Section 5.3. Next, an attempt to improve these results led to the simple
optimization schemes, presented in Section 7.3, where the system's operation was based
on minimizing cost, PEC, or CDE. Then, the operation of the cutoff strategies from
Section 5.3, FELc and FTLc, were explored. For the CCHP system, additional
simulations were performed using the average electricity price and average natural gas
price, and the price of exported electricity was investigated. All the above simulations
were performed using three different natural gas engine sizes as the prime mover: a 6-
kW unit, a 8.5-kW unit, and a 12-kW unit, with the minimum load of each engine taken
to be 25% of the full load. The CCHP and CHP system parameters and the prime mover
characteristics are presented in Table 9.1 and Table 9.2.

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Table 9.1   CCHP and CHP system parameters

Parameter	Value
Boiler efficiency	0.9
Heat recovery system efficiency	0.8
Heating coil efficiency	0.9
Chiller COP (CCHP system)	0.7
Vapor compression COP (CHP system)	3.05

Table 9.2   Prime mover characteristics for the 6-kW, 8.5-kW, and 12-kW natural gas engine

	6 kW	8.5 kW	12 kW
Max PGU load, L, (kW)	6	8.5	12
Min PGU load (%)	25	25	25
Min PGU load, E_{min} (kW)	1.5	2.125	3.0
Max PGU efficiency = L/F_{pgu}	0.220	0.221	0.211
Min PGU efficiency = E_{min}/F_{pgu}	0.078	0.095	0.111
Max recoverable heat (kW)	17.04	24.03	35.91
Min recoverable heat (kW)	14.16	16.12	19.26
PGU coefficient, α	1.8[a]	2.551[b]	3.312[b]
PGU coefficient, β	16.5[a]	16.862[b]	17.145[b]

[a]Theoretical values
[b]Kholer residential generator sets [41]

Of the sixteen locations that are available for the benchmark building, three cities with different electricity rate structures were chosen: Boulder, CO, Duluth, MN, and Chicago, IL. From the hourly simulation data of the reference building, the average and maximum electric and heating requirements for each city are provided in Table 9.3.

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Table 9.3   Average and maximum hourly electric and heating requirements for Boulder, Duluth, and Chicago

		Boulder		Duluth		Chicago	
		E_{req}	Q_{req}	E_{req}	Q_{req}	E_{req}	Q_{req}
CCHP system	Average (kWh)	7.73	5.15	8.14	7.61	7.69	6.98
	Max (kWh)	14.78	35.44	15.42	44.46	15.05	42.93
CHP system	Average (kWh)	8.42	1.99	8.50	4.75	8.51	4.74
	Max (kWh)	22.05	31.18	22.19	36.00	23.54	30.10

The electricity rate structures along with other cost data for Boulder, Duluth, and Chicago are presented in Table 9.4, Table 9.5, and Table 9.6. In Boulder, the office building faces a constant energy charge rate. The office building in Duluth experiences seasonal electric rates, where there is a different energy charge rate in the summer months than in the winter months. The Chicago office uses a constant energy charge rate in addition to block charges. Table 9.4, Table 9.5, and Table 9.6 also give the average electricity price, average natural gas price, and the standard deviation of the monthly natural gas prices for the three cities. The average electricity and natural gas prices are those observed by the reference case. For example, the average electricity price is the annual electric bill of the reference building divided by the reference building's annual electricity consumption. The standard deviation of the monthly natural gas prices helps to give a sense of the month-to-month variation in natural gas prices. The PEC and CDE conversion factors for the different locations are listed in Table 9.7.

Table 9.4   Boulder cost data [35]

Parameter	Value
Energy charge, r_e ($/kWh)	0.0705
Monthly charge ($)	6.60
Taxes, t (%)	4.9
Average electricity rate ($/kWh)	0.075082
Average natural gas rate ($/kWh)	0.023932
Average natural gas rate ($/MCF)	7.21712
Std deviation of monthly natural gas rates ($/MCF)	0.463

Table 9.5   Duluth cost data [35]

Parameter	Value
Summer energy charge*, r_e($/kWh)	0.0758
Winter energy charge**, r_e ($/kWh)	0.0658
Monthly charge ($)	6.88
Taxes, t (%)	6
Average electricity rate ($/kWh)	0.074500
Average natural gas rate ($/kWh)	0.028893
Average natural gas rate ($/MCF)	8.71320
Std deviation of monthly natural gas rates ($/MCF)	0.551

* June - September
** October - May

Table 9.6   Chicago cost data [35]

	Size (kWh)	Cost ($/kWh)
Block 1	300	0.082409
Block 2	700	0.072873
Block 3	1500	0.061696
Block 4	remaining	0.041179
Energy charge, r_e ($/kWh)	0.00435	
Monthly charge ($)	9.40	
Taxes, t (%)	8	
Average electricity rate ($/kWh)	0.062159	
Average natural gas rate ($/kWh)	0.029043	
Average natural gas tate ($/MCF)	8.758412	
Std deviation in natural gas prices ($/MCF)	0.99	

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Table 9.7   PEC and CDE factors for Boulder, Duluth, and Chicago [35]

		CF_{PEC} (kWh/kWh)	CF_{CDE} (g/MJ)
Electricity	Boulder, CO	3.318	264.4
	Duluth, MN	3.437	219.2
	Chicago, IL	3.546	341.7
Natural Gas		1.092	52.1

9.1   CCHP System under Continuous Operational Strategies

The results from operating the 6-kW, 8.5-kW, and 12-kW engines using FEL, FTL, and constant load (E_{min} and L) strategies are displayed in Figure 9.1 for Boulder, Duluth, and Chicago. Examination of the engine size demonstrates that for a given continuous operational strategy in any one of the evaluated cities, as the engine size increases the resulting cost and PEC also increase. This is because the larger engine consumes more fuel and the additional heat produced from the larger engine is not fully utilized. However, this trend was not present in the CDE results, where the engine size yielding the lowest emissions depends on the operational strategy and location.   This is due to the low carbon dioxide emission factor for natural gas compared to those for electricity. Full-load and FEL operation tend to have the greatest spread in cost and PEC results among engine sizes. These are the strategies that consume the most fuel and use the least amount of grid electricity.

The best operating strategy will depend on the engine size, location, and objective of the facility. For example, if cost or perhaps emissions is the most important factor. Table 9.8 presents the top two strategies in each performance metric and engine size for

the evaluated cities. This table was built using the results presented in Table 9.7. Operating at full load provides for the lowest CDE. This is because more electricity is produced on-site, which reduces the amount of electricity that has to be generated at the power plant and natural gas combustion is less polluting than the average power plant. Full-load operation also provides the best PEC results for the 6-kW and 8.5-kW engines. On the other hand, FTL operation is the lowest PEC strategy and lowest cost strategy for the 12-kW engine. The lowest cost strategy for the 6-kW and 8-kW engine is FEL, except for the 8-kW engine in Chicago where FTL gives the lowest cost.
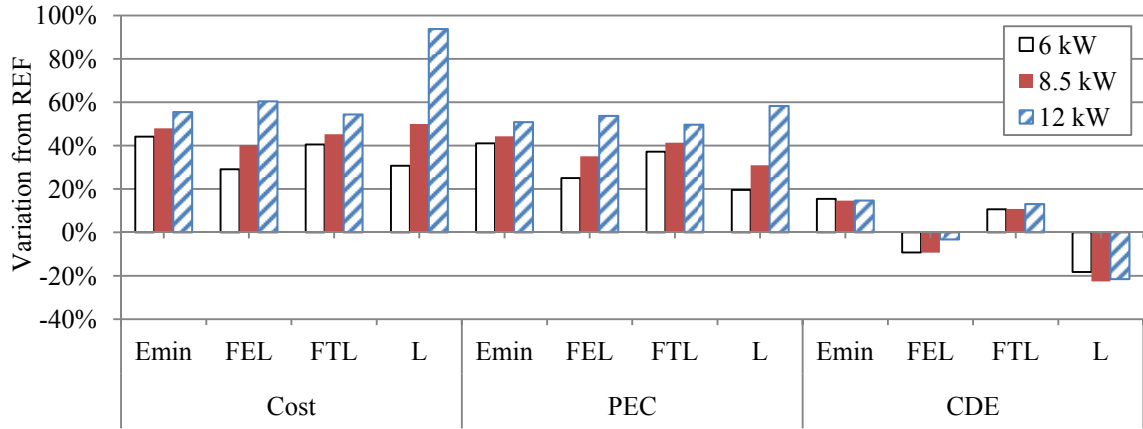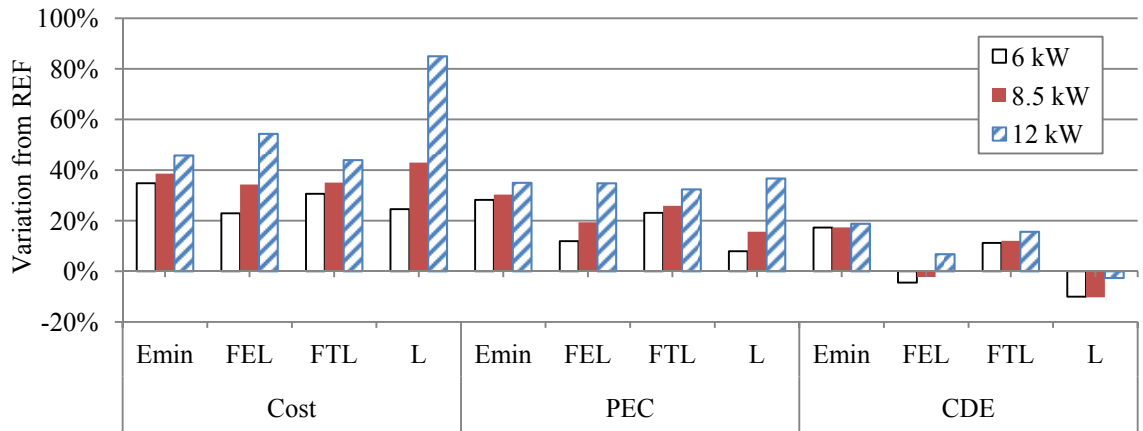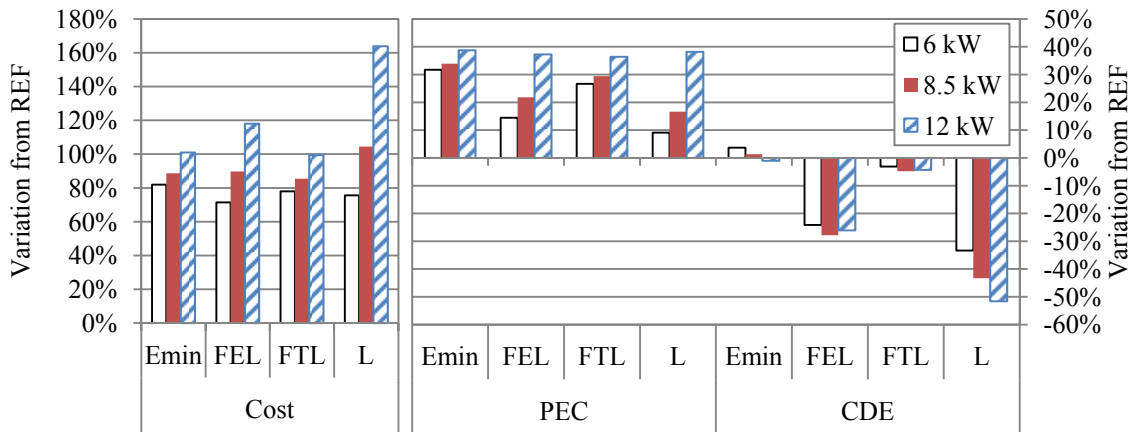
Figure 9.1   CCHP system performance operating under the continuous strategies in (a) Boulder, (b) Duluth, and (c) Chicago

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Table 9.8   Top two continuous strategies in each performance metric by engine size (Values given in percent variation from the reference case)

	Boulder			Duluth			Chicago		
	Cost	PEC	CDE	Cost	PEC	CDE	Cost	PEC	CDE
6 kW	FEL (29.1) L (30.7)	L (19.6) FEL (25.1)	L (-18.2) FEL (-9.3)	FEL (22.9) L (24.5)	L (7.9) FEL (11.9)	L (-10.0) FEL (-4.5)	FEL (71.4) L (75.6)	L (9.1) FEL (14.4)	L (-33.3) FEL (-24.1)
8 kW	FEL (40.2) FTL (45.2)	L (30.9) FEL (35.1)	L (-22.6) FEL (-9.3)	FEL (34.3) FTL (35.1)	L (15.6) FEL (19.4)	L (-10.3) FEL (-2.3)	FTL (85.4) E_{min} (88.7)	L (16.7) FEL (21.8)	L (-43.3) FEL (-27.8)
12 kW	FTL (54.4) E_{min} (55.5)	FTL (49.6) E_{min} (50.9)	L (-21.5) FEL (-3.2)	FTL (44.0) E_{min} (45.8)	FTL (32.4) FEL (34.8)	L (-2.7) FEL (6.8)	FTL (99.4) E_{min} (101.0)	FTL (36.4) FEL (37.2)	L (-51.6) FEL (-26.1)

In all the evaluated cities, regardless of engine size or operational strategy, the cost and PEC are higher than the reference case and significantly higher in many cases. The CDE emissions depend on the location, strategy, and engine size as to whether they are better than the reference case. More closely examining the fuel and electricity consumption of the CCHP system can explain these trends. Taking the 8-kW CCHP system in Boulder as an example, Figure 9.2 reveals that the CCHP system consumes less electricity than the reference case but significantly more fuel energy.
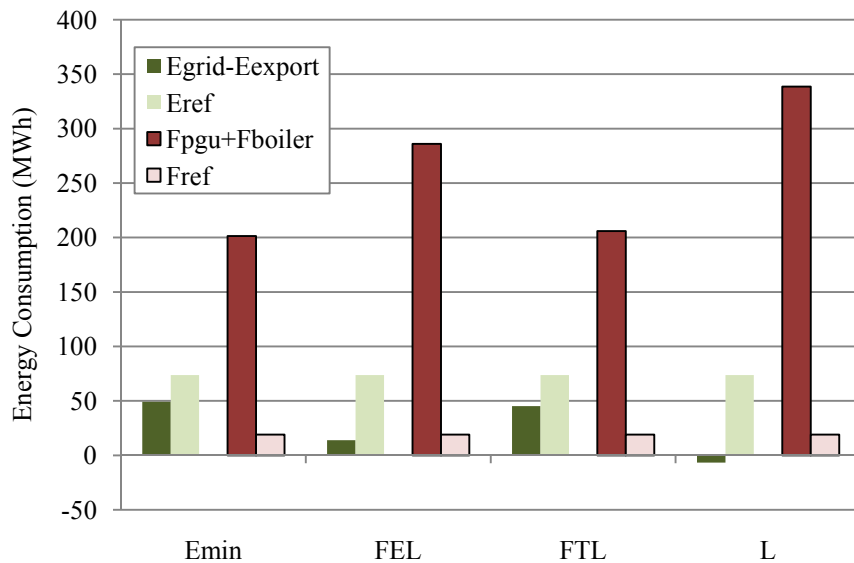
Figure 9.2   Electricity and natural gas consumption of the CCHP system and the reference building

Considering PEC, in order for the CCHP system to maintain or reduce the reference building's primary energy consumption, the decrease in electricity primary energy consumption must be greater than or equal to the increase in fuel primary energy consumption. In other words,

$$\left[E_{ref} - (E_{grid} + E_{export})\right]CF_{PEC,e} \geq \left[(F_{pgu} + F_{boiler}) - F_{ref}\right]CF_{PEC,ng} \qquad (9.1)$$

where E_{ref} and F_{ref} are the electricity and natural gas consumption, respectively, of the reference case. Rearranging the above equation yields

$$\frac{(F_{pgu} + F_{boiler}) - F_{ref}}{E_{ref} - (E_{grid} + E_{export})} \leq \frac{CF_{PEC,e}}{CF_{PEC,ng}} \qquad (9.2)$$

When this inequatility is true, the PEC of the CCHP system will be less than or equal to the PEC of the reference case. The same thought process can be carried out for CDE resulting in the emission conversion factors replacing the PEC conversion factors of Equations (9.1) and (9.2). Cost is not as simple due to varying rates, monthly charges, and taxes, but can be estimated by using the ratio of average natural gas price (in \$/kWh) to average electricity price in Equation (9.1) and (9.2). The ratio of the reduced electricity consumption to the increase in natural gas consumption can be defined as γ, or

$$\gamma = \frac{(F_{pgu} + F_{boiler}) - F_{ref}}{E_{ref} - (E_{grid} + E_{export})} \qquad (9.3)$$

Also, the natural gas to electricity ratio of average prices, PEC conversion factors, and CDE conversion factors can be defined using φ as follows

$$\varphi_{cost} \leq \frac{p_e}{p_{ng}} \qquad (9.4)$$

$$\varphi_{PEC} \leq \frac{CF_{PEC,e}}{CF_{PEC,ng}} \qquad (9.5)$$

$$\varphi_{CDE} \leq \frac{CF_{CDE,e}}{CF_{CDE,ng}} \qquad (9.6)$$

A general form of Equation (9.2) can now be expressed as

$$\gamma \leq \varphi \qquad (9.7)$$

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Figure 9.3 indicates that for cost and PEC, γ is not lower than φ; therefore, the decrease in cost and PEC as a result of a decrease in grid consumption is not enough to overcome the increase in cost and PEC due to an increase in fuel consumption. This is also the case for CDE under the E_{min} and FTL strategies. But, γ is less than φ_{CDE} during full-load and FEL operation, so the decreased grid consumption results in lower CDE than the reference case.

Alternatively, Equation (9.7) can be used to find the needed φ_{cost} that would make the inequality of Equation (9.7) true. For example, the ratio of electricity price to natural gas to would need to increase from 3.1 to 4.5 in order for the 8-kW FEL-CCHP system in Boulder to be on par with the costs of the reference case. This could be accomplished with a decrease in natural gas prices, an increase in electricity prices, or a combination of the two.
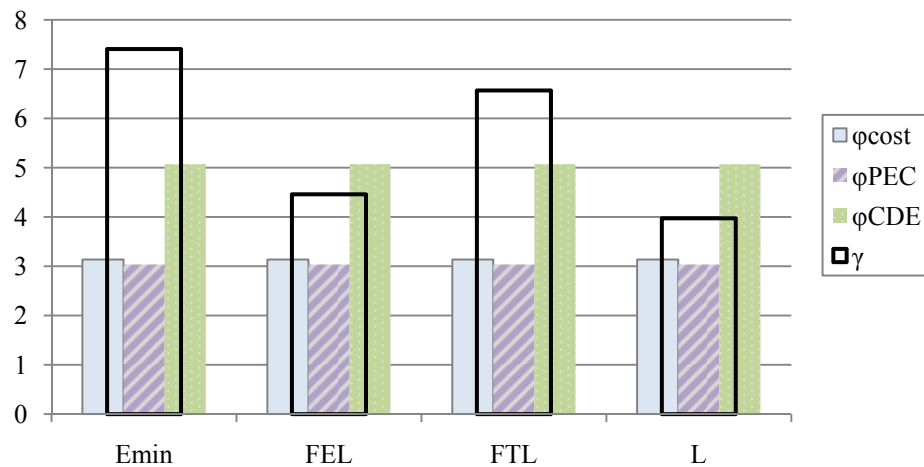
Figure 9.3 γ versus φ for the 8-kW engine in Boulder

All the strategies cost at least 23% more than the reference case, with the Chicago CCHP system having extremely high costs when compared to the reference building (over 75% higher). Chicago is the most costly city to operate the CCHP system due to the nature of Chicago's block charges. Under this type of schedule, the price of electricity and, therefore, the average price of electricity decreases as consumption increases. However, operation of the CCHP significantly decreases the electric consumption from that of the reference building and, therefore, the office with a CCHP system must pay a higher average price than the reference building. In general, PEC in Boulder saw the highest increases from the reference case (20-58%, depending on the engine size), followed by Chicago (9-39%), then Duluth (8-37%). Concerning CDE, reductions from the reference case were attainable. In Chicago, emissions were 33-52% lower than the reference case for full-load operation, about 26% less for FEL operation, and about 5% less for FTL operation. Boulder's emission were about 20% less than the reference case for full-load operation and 3-9% less for FEL operation. Finally, in Duluth emissions were reduced from the reference case by about 3-10% while operating at full load and marginally lower for the 6-kW and 8.5-kW engine under the FEL strategy. Unfortunately, in these cities the benefits of reduced emissions from the reference case are somewhat negated by the large increase in operational cost. However, if financial gain resulted from the reduction in emissions, the CCHP system would be more attractive.

9.2   CCHP System Optimization

Figure 9.4 presents the optimization results of the CCHP system with respect to the reference case. While these results are compared to the reference case, the optimized CCHP system is optimized relative to a non-optimized CCHP system. The engine size affects the performance of the optimized CCHP system, with better performance generally occurring as the engine size decreases. Exceptions occur for the CDE results of the PEC optimized system and the CDE optimized system in Boulder and Duluth. For these exceptions, the 8-kW engine performs the best, followed closely by the 6-kW engine, and then the 12-kW engine. Figure 9.4 also reveals that for a given city, the results for the cost optimization and PEC optimization are very close, with the largest difference being a few percentage points.

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(a)

(b)

(c)
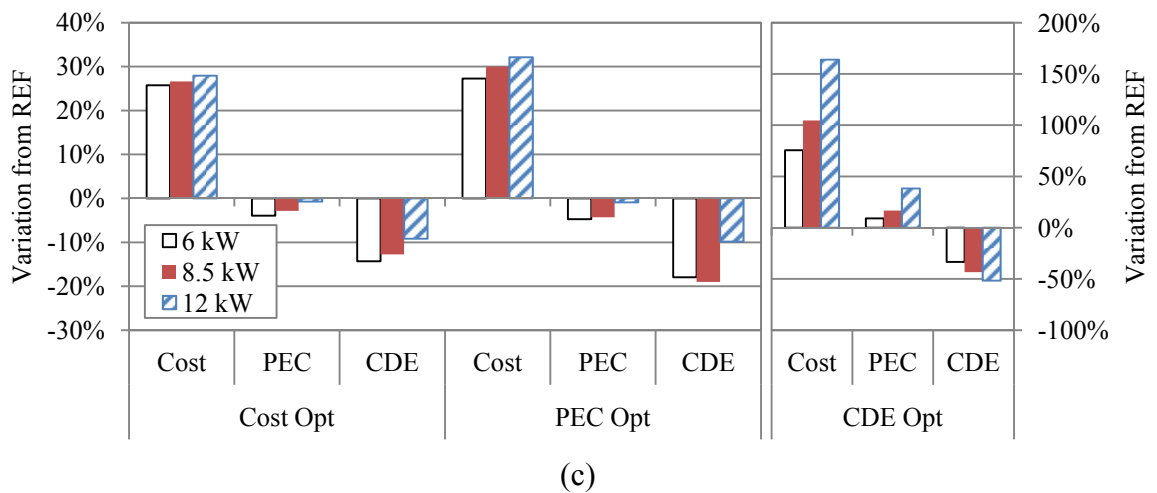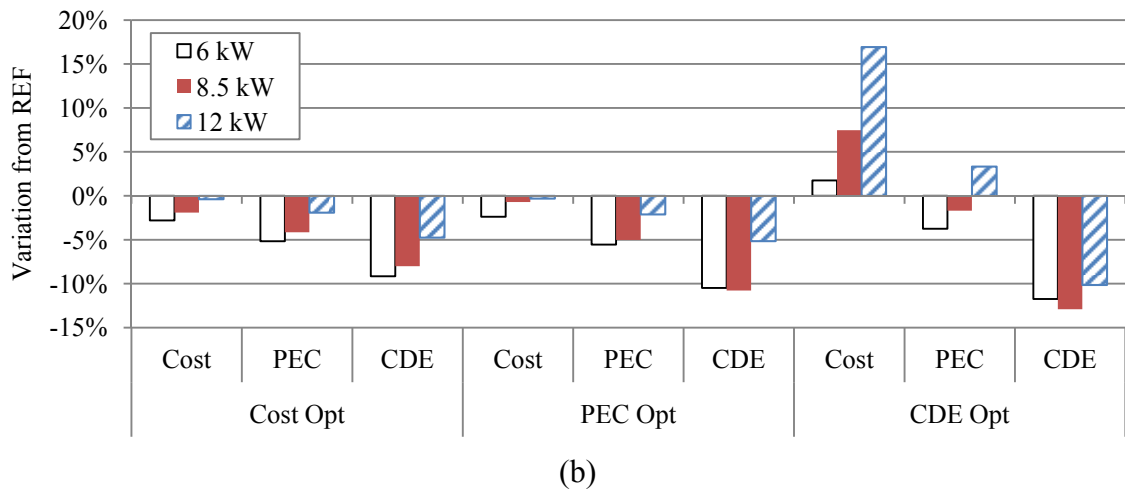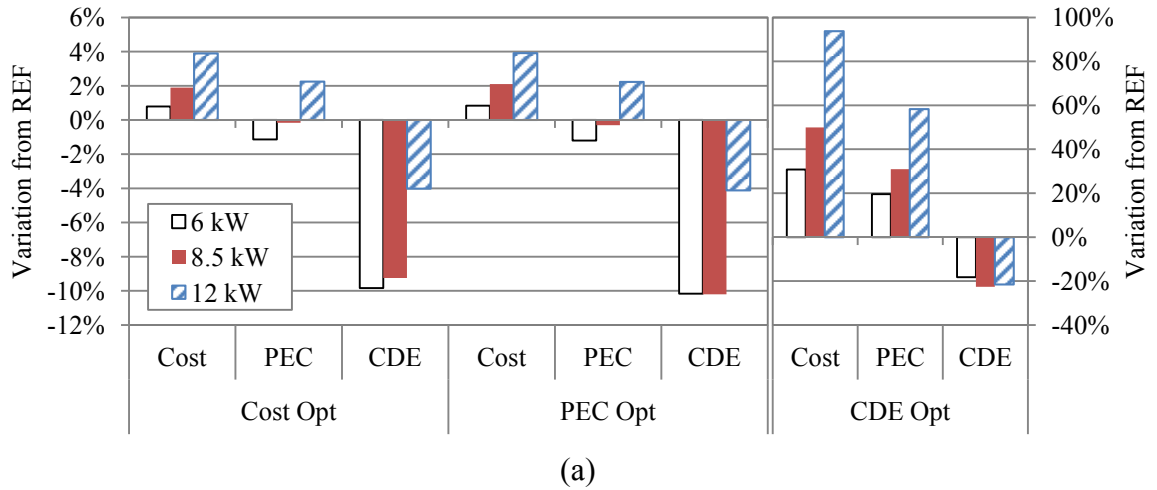
Figure 9.4   Performance of the CCHP system optimized for cost, PEC, and CDE in
            (a) Boulder, (b) Duluth, and (c) Chicago

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As illustrated in Figure 9.5, for Boulder, Duluth, and Chicago optimizing the CCHP system to minimize cost or PEC can provide significant improvements in performance over the continuous operational strategies (Figure 9.1). In Duluth, for example, optimizing costs reduces the operational costs on average by 26% from the lowest cost continuous strategy. Similarly, PEC optimization in Duluth results in an average of 19% reduction in the PEC. The CDE optimization in Duluth provided a slight improvement over the CDE results from full-load operation; but, in terms of the associated cost and PEC, the CDE optimization in Duluth yielded better results than the full-load operation. On the other hand, CDE optimization in Boulder and Chicago essentially resulted in the engine operating at full load continuously and, thus, did not provide any improvement over the full-load operational strategy.
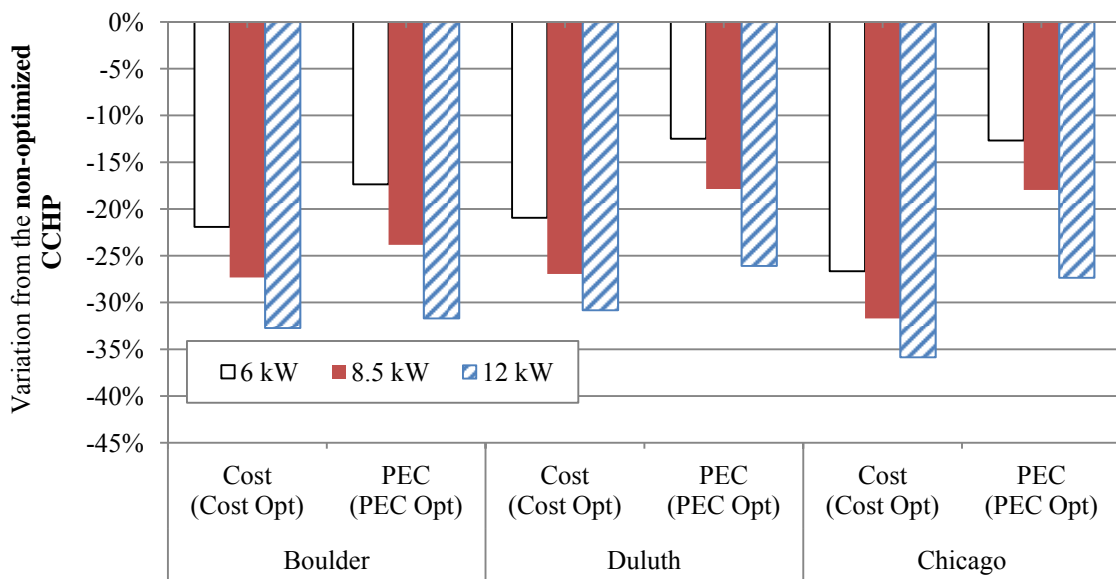
Figure 9.5   Cost and PEC results from the cost- and PEC-optimized CCHP system
              with respect to, respectively, the lowest cost and lowest PEC results of
              the non-optimized CCHP system

In Boulder, the 6-kW, 8-kW, and 12-kW cost-optimized systems still have about 1%, 2%, and 4% higher costs, respectively, than the reference case. For the cost- and PEC- optimized cases, slight reductions in PEC are obtainable for the 6-kW and 8-kW engines, while all of the engine sizes under any optimization reduce the CDE. Operating the system to minimize cost or minimize PEC in Duluth achieves 0-3% reductions in cost, 2-4% reductions in PEC, and 5-10% reductions in CDE. In Chicago, optimizing for cost and PEC yielded very small PEC reductions from the reference case along with 10-19% reductions in CDE. The resulting costs are about 30% higher than the reference case, but they are less than half of the cost for the continuous operational strategies.

Corresponding with Figure 9.4 for optimization of the CCHP system, Figure 9.6 gives additional performance indicators for the optimized system and provides insight into its operation. Under the different optimization strategies, these figures present the fraction of the year that the CCHP system is operating (On), the CCHP system efficiency (η_{CCHP}) defined by Equation (7.19), and the overall building efficiency (η_B) defined by Equation (7.20). Optimizing the system to minimize cost or minimize PEC results in superior performance over the continuous strategies because the system turns off when it is beneficial to do so. Reducing the engine size tends to increase the operating time, and the order of increasing operating time among the optimization criteria was cost, PEC, and CDE. Minimizing costs or primary energy resulted in CCHP system efficiency values that range from about 60 to 70%. Duluth achieved the highest CCHP efficiency, about 72.3% for the 12-kW cost optimization. However, minimizing CDE only resulted in CCHP efficiencies between 28 and 35% in Boulder, 29 and 37% in Chicago, and 45 and

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54% in Dulluth. With the exception of CDE optimization in Boulder and Chicago, the overall building efficiency falls between 37% and 41%; this is consistent with the overall building efficiency of the reference case.

(a)

(b)

(c)
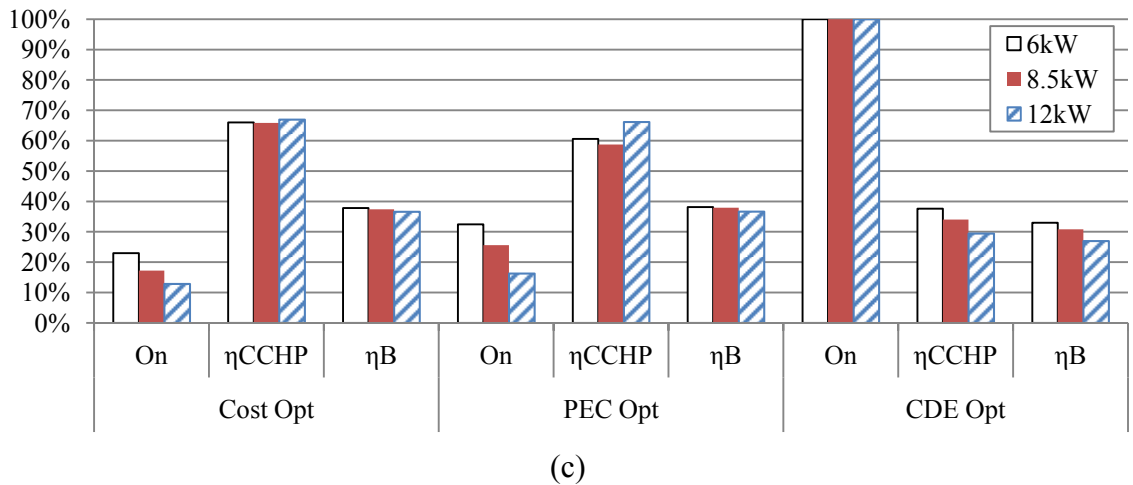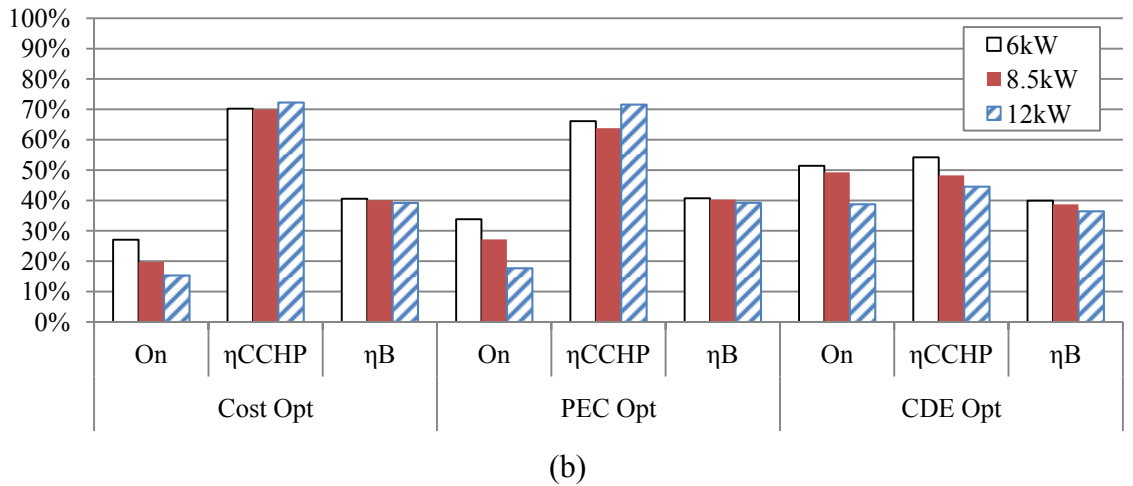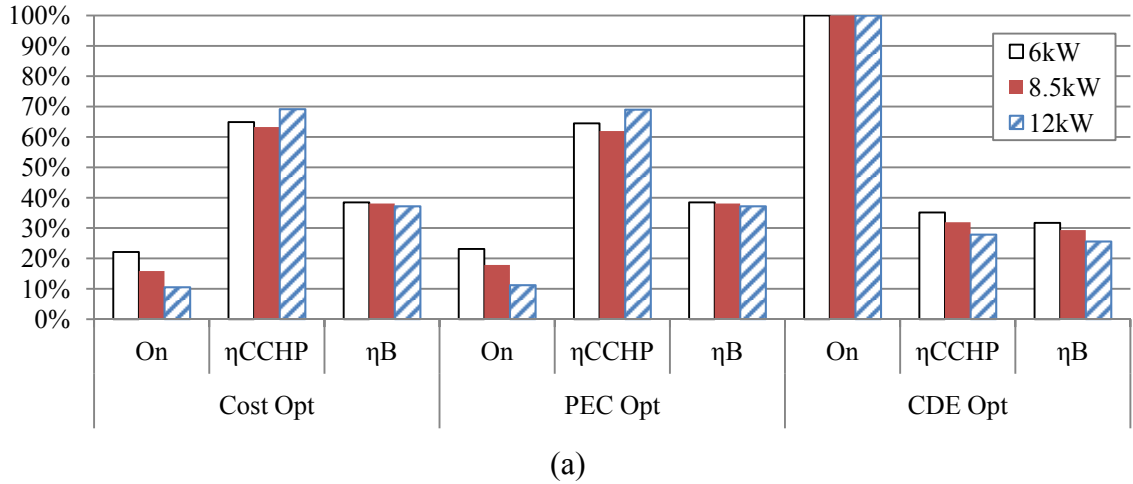
Figure 9.6   Operating time, CCHP system efficiency, and overall building efficiency
                 of the system optimized for cost, PEC, and CDE in (a) Boulder, (b)
                 Duluth, and (c) Chicago

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9.3   CCHP System under the Cutoff Strategies

The optimized cases proved that reducing the operating time could benefit the CCHP system. Therefore, simulations of the FELc and FTLc strategies were compared to the FEL and FTL strategies, with the results presented in Figure 9.7. The 6-kW engine operating to FELc strategy does not improve the performance over the FEL strategy because the required electric load never drops below the minimum engine load. The 8.5-kW and 12-kW engines, operating to FELc provides a slight improvement over the FEL strategy. The FTLc strategy, however, provides a significant improvement over the FTL strategy. This is because turning the engine off when the required heat is below the minimum heat recoverable from the engine reduces the amount of unused heat and fuel consumption. The resulting cost and PEC from the FTLc strategy is within 1.2% of the cost and PEC results of the cost-optimized system with this percent difference decreasing as the engine size increases. Plus, the FTLc strategy would be a simpler strategy to follow, especially for locations with complex utility structures.

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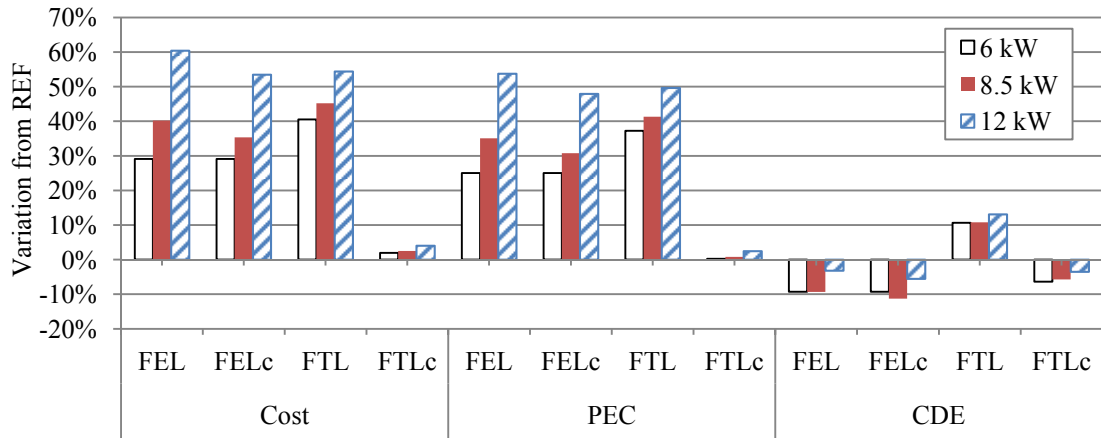
(a)
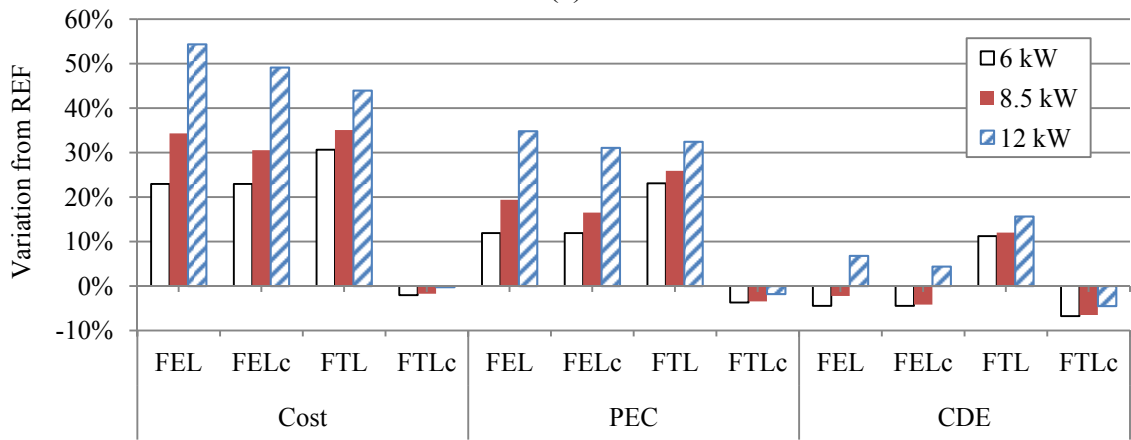
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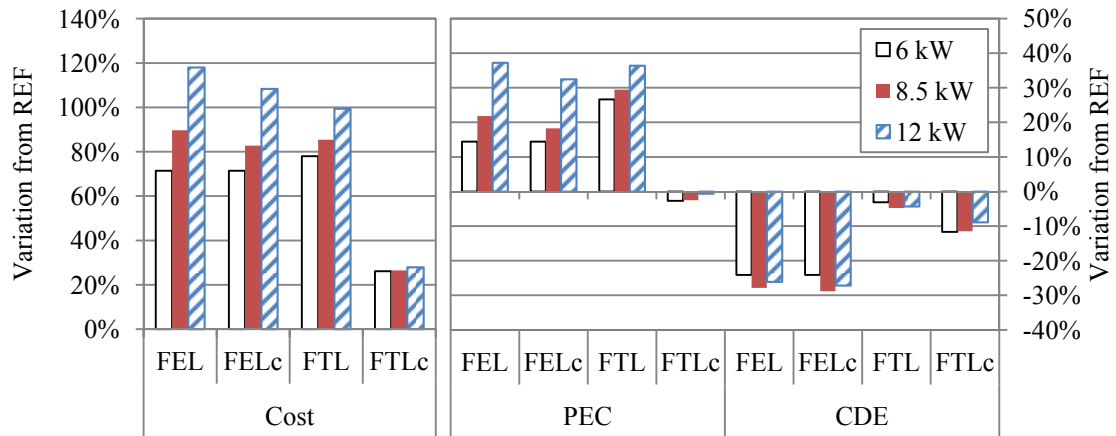
(c)

Figure 9.7   Comparison of FELc and FTLc to FEL and FTL for (a) Boulder, (b) Duluth, and (c) Chicago for the CCHP system

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9.4 Real Prices versus Average Prices during CCHP Modeling

This section examines the effect of the values used for the electricity and natural gas prices on the operating cost for the CCHP system. The operational cost calculated using the actual electricity and natural gas prices was compared to those calculated using the average price values for electricity and natural gas during the continuous operational strategies and the cost optimization scheme in all three cities. For the results, each figure has bars that represent the operational costs using actual prices, previously presented in either Figure 9.1 or Figure 9.4. In addition, there are three markers: one represents the costs calculated using the average electricity price (with actual natural gas prices), one is from using the average natural gas price (with actual electricity rates), and the last marker is the resulting cost from using both the average electricity price and the average natural gas price. As a reminder, the average price values that were used here are with respect to the reference case and the use of national averages instead of local averages could have a more significant impact on the deviation of the operational cost calculated from using actual prices.

For the continuous operational strategies in Boulder, Figure 9.8, the results from using an average electricity rate hardly deviate from using the actual utility rate structure. A very slight underestimation of the cost is present for the cases where the grid electricity consumed by the CCHP system is significantly lower than that for the reference case, such as full-load and FEL operation. On the other hand, using an average natural gas rate noticeably underestimates the operational costs of the CCHP system. This underestimation is lower for the same strategies mentioned before that consume less electricity than the reference building, thereby consuming more natural gas. When

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combined, the percent difference between using average rates and actual rates is at least 5.8%, which increases as the engine size increases. The highest underestimation of the actual cost that results from using average prices is 12.3% and occurs for the 12-kW engine running at full load. For the cost-optimized system in Boulder, Figure 9.8 proves that using average prices results in the predicted costs being about 3 to 4% lower than the predicted costs from using actual prices. This difference lowers the cost for the 6-kW and 8.5-kW engines so that the CCHP system appears favorable when compared to the reference case while in actuality that is not the case.
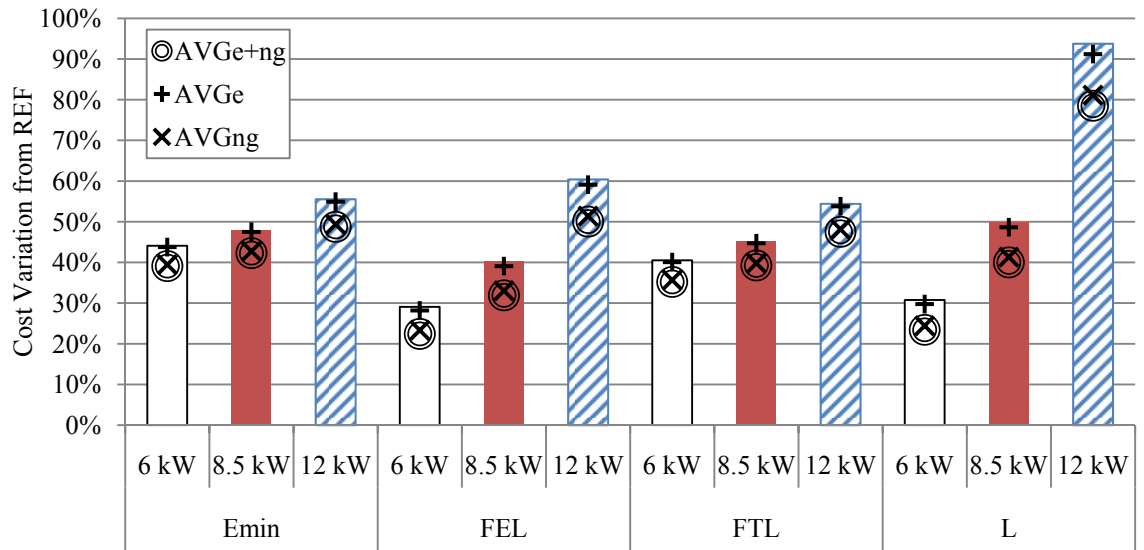
(a)
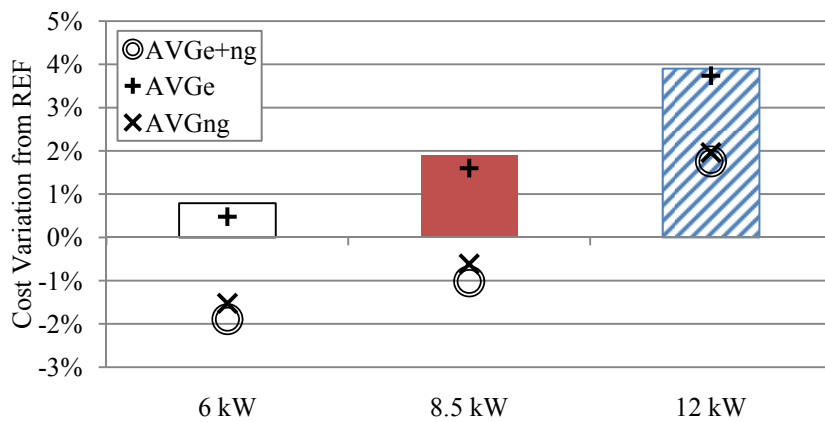
(b)

Figure 9.8.   Comparison of using average prices to actual rates for (a) the continuous
              strategies and (b) the cost-optimized CCHP system in Boulder

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Figure 9.9(a) for the continuous operating strategies in Duluth reveals that, like Boulder, a very slight underestimation of the cost due to using an average electricity price is noticeable for those strategies where the grid electricity consumed by the CCHP system is notably lower than that for the reference building. However, unlike in Boulder, using an average natural gas price slightly overestimates the actual prices. This has to do with the timing and quantity of natural gas consumption. How much natural gas the system consumes and whether the average natural gas price is higher or lower than the actual price for that month dictates the magnitude of overestimation or underestimation. Overall, employing average prices to compute the cost in Duluth results in costs that are 1.6 to 2.5% higher than the actual costs. Average price data cause deviations of about 1% for the cost-optimized system in Duluth, Figure 9.9(b).
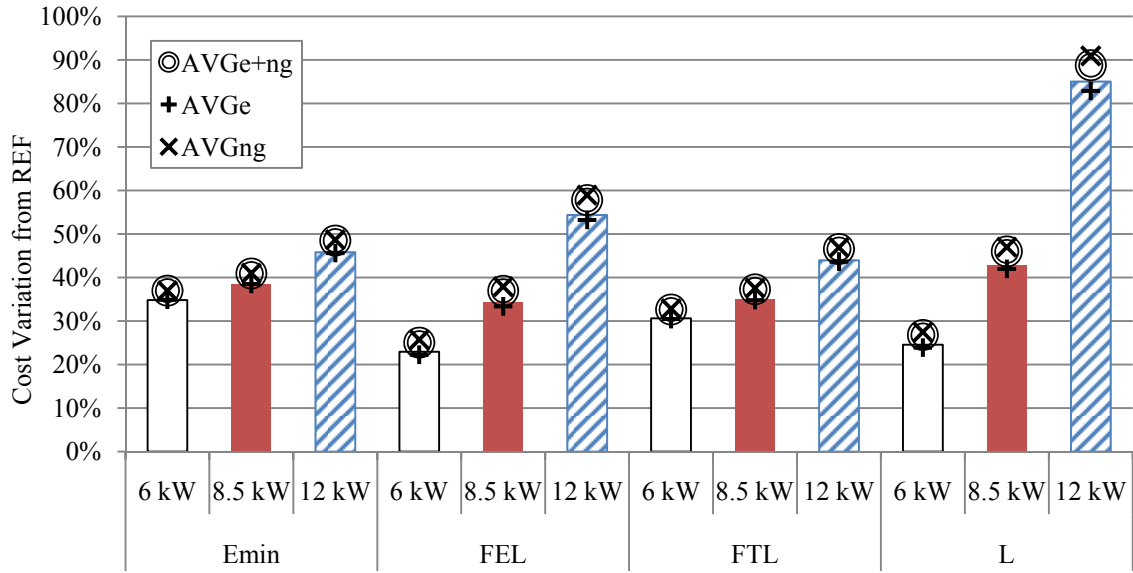
(a)
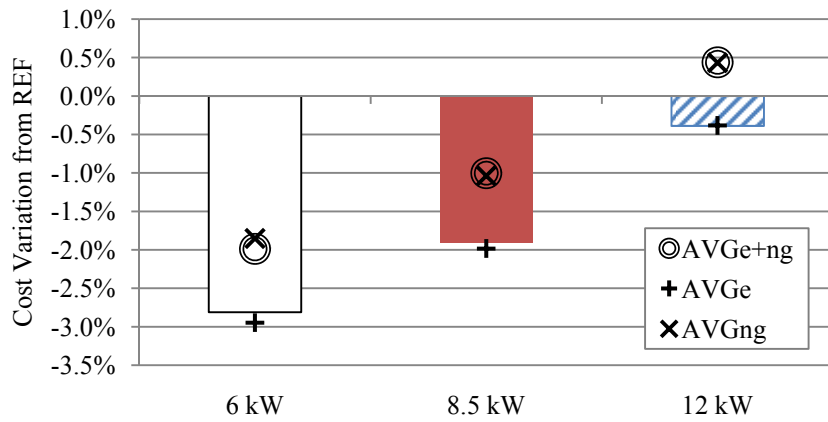
(b)

Figure 9.9   Comparison of using average prices to actual rates for (a) the continuous strategies and (b) the cost-optimized CCHP system in Duluth

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Figure 9.10(a) for Chicago illustrates that using an average electricity price results in a more noticeable underestimation of cost from using the actual utility structure, with the exception of the 12-kW engine at full load. The cost underestimation is due to the block structure, which is set up so the average electricity rate decreases as more electricity is consumed. The exception of the 12-kW engine at full load reflects profits from selling electricity back to the grid. The average natural gas price also underestimates the true costs, which compounds the underestimation due to the average electricity price. Overall, the costs are low by 6.9 to 13.5% when average electricity and gas prices are assumed for Chicago. In addition, large deviations are present in the cost-optimized system, which drastically affects the perception of the CCHP system in Chicago. This is demonstrated in Figure 9.10(b). Assuming average prices leads to the cost-optimized CCHP system having about 10% higher costs than the reference building. This combined with lower PEC and CDE (Figure 9.4(c)) might lead to the implementation of such a system. However, when actual rates are considered this conclusion is not likely since the cost of the CCHP system would be almost 30% higher than the reference building.
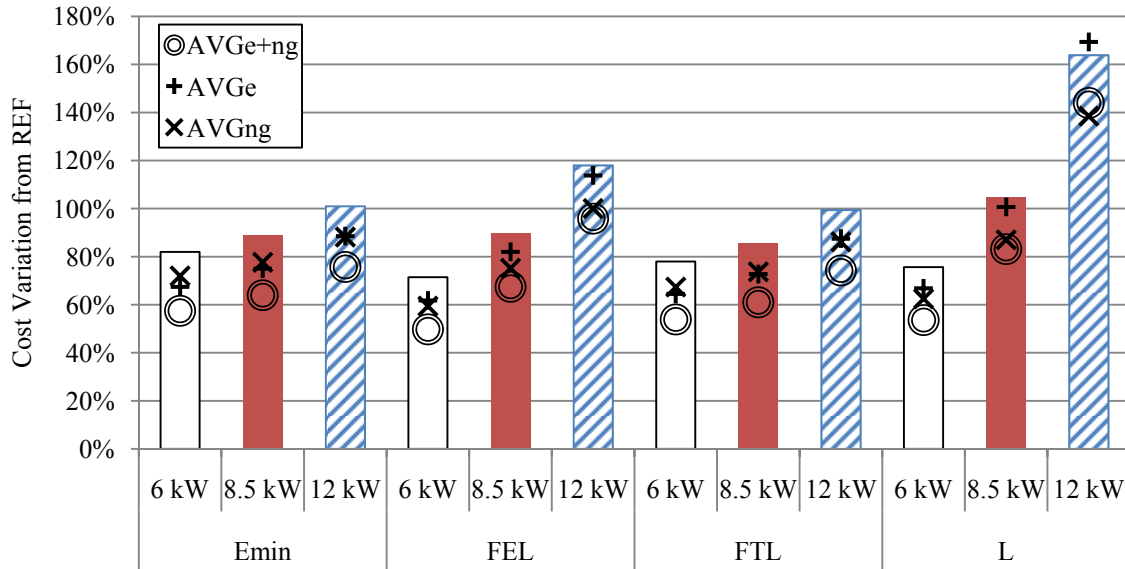
(a)
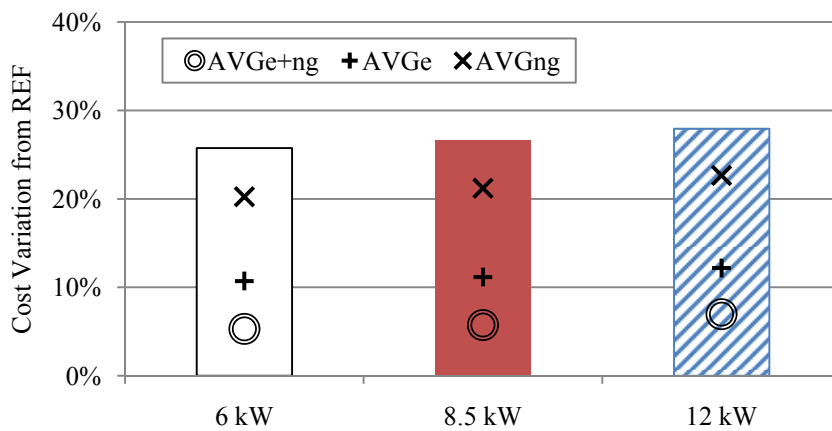
(b)

Figure 9.10   Comparison of using average prices to actual rates for (a) the continuous
strategies and (b) the cost-optimized CCHP system in Chicago

9.5   Effect of Electricity Export Price during CCHP Modeling

This section seeks to investigate the effect of the electricity export price on

operational costs. In addition to receiving half the value of imported electricity for

exported electricity (50%) as was previously done, simulations were also performed for

the case of no exporting (0%) and for full-price exporting (100%). From Figure 9.11, the

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price of exported electricity does not have a noticeable effect on operational costs for the E_{min}, FEL, and FTL strategies, but the export price does have an impact during full-load operation causing the operational costs to decrease as the export price increases. Moreover, as the engine size increases this effect becomes more important. For full-price exporting, full-load operation becomes the least-cost operating strategy for the 6-kW and the 8-kW engines in Boulder and Duluth. Similarly, Figure 9.12 establishes that for the cost-optimized strategy, the export price has little to no effect on the operational costs. This is because the amount of electricity exported is only a small fraction when compared to the amount consumed.

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(a)

(b)

(c)
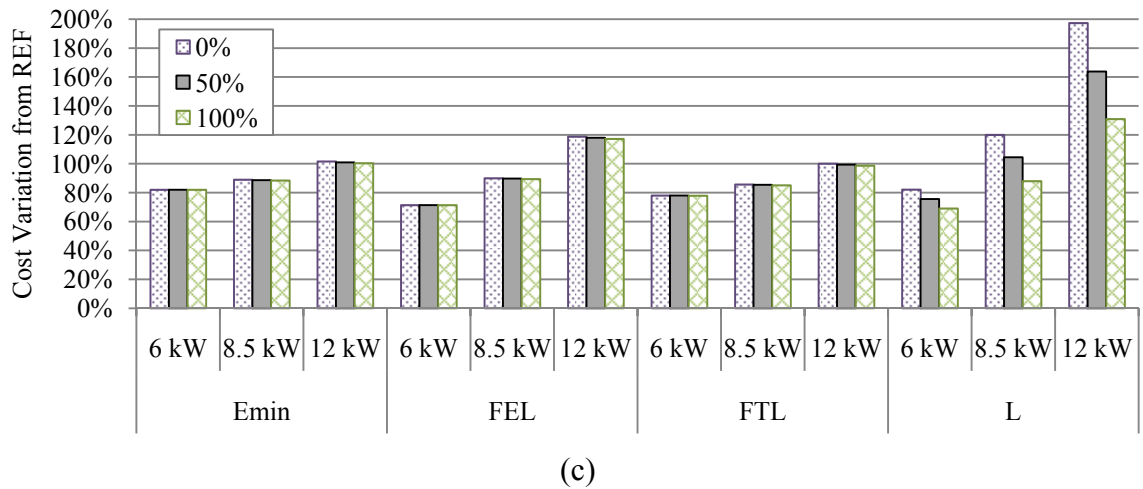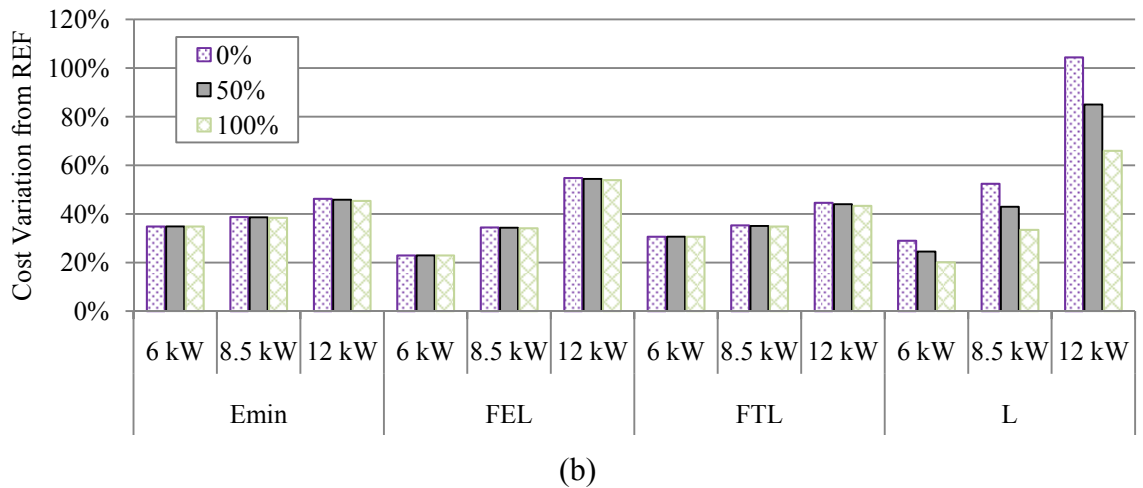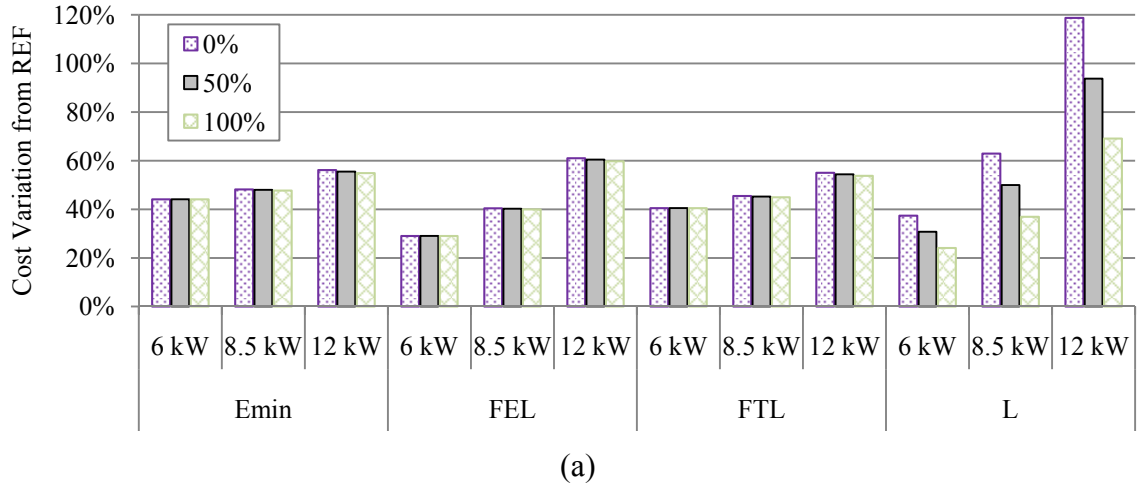
Figure 9.11   Effect of electricity export price on cost for the continuous operational
strategies in (a) Boulder, (b) Duluth, and (c) Chicago

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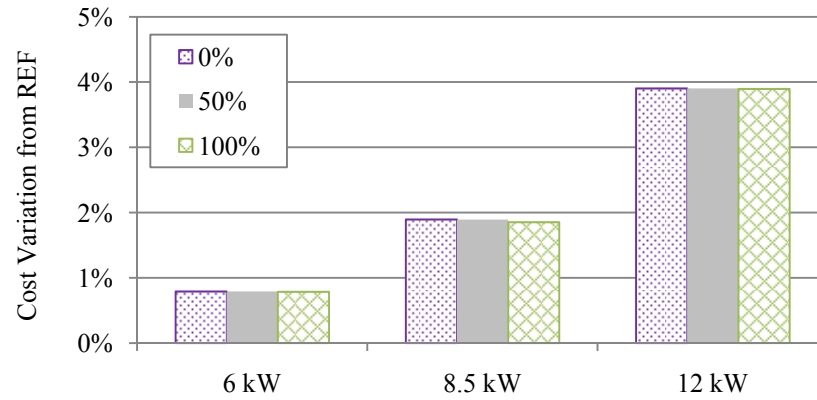
(a)
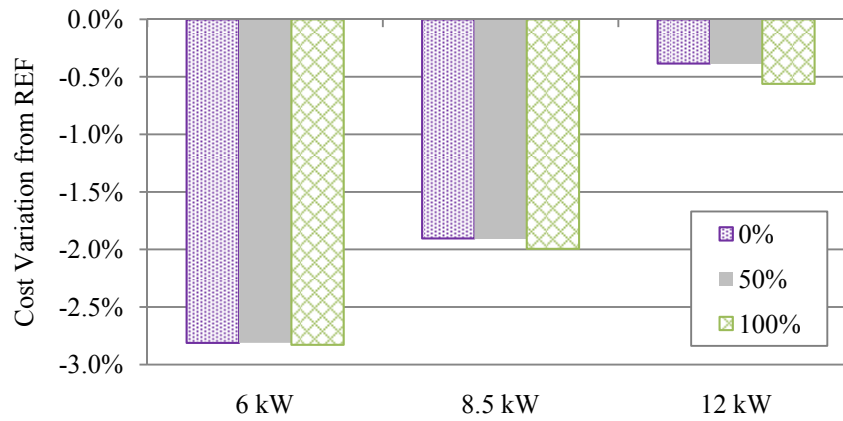
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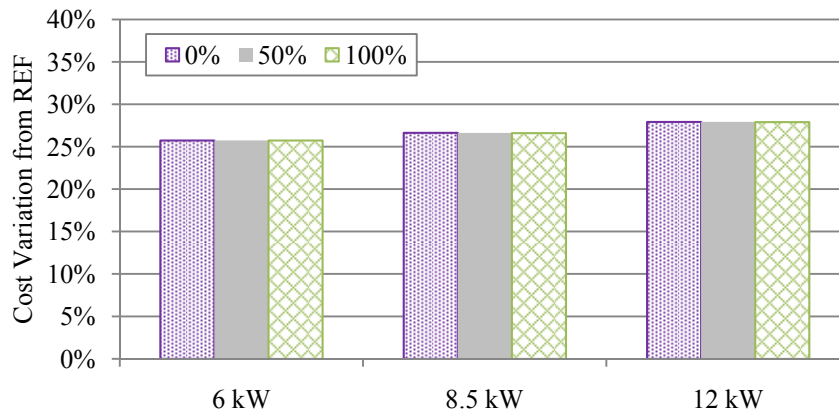
(c)

Figure 9.12   Effect of electricity export price on cost during cost optimization in (a) Boulder, (b) Duluth, and (c) Chicago

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9.6   CHP System under Continuous Operational Strategies

Cost, PEC, and CDE results for the CHP system operating under the continuous operational strategies are compared to the reference case in addition to the CCHP system results, and when comparing the CHP system to the CCHP system both systems are using the same operational strategy.

Operating the CHP system under the continuous operational strategies produces similar results as the CCHP system operating under the same strategies. However, the performance of the CHP system under these strategies is worse than that for the CCHP system under the same strategies, as can be seen in Figure 9.13, which gives the cost, PEC, and CDE for the CHP system as the percent variation from the CCHP system. The CCHP system performs better under the continuous strategies because both systems are running continuously and the CCHP system is able to utilize more waste heat, especially in the summer months, to satisfy the cooling load via the absorption system.
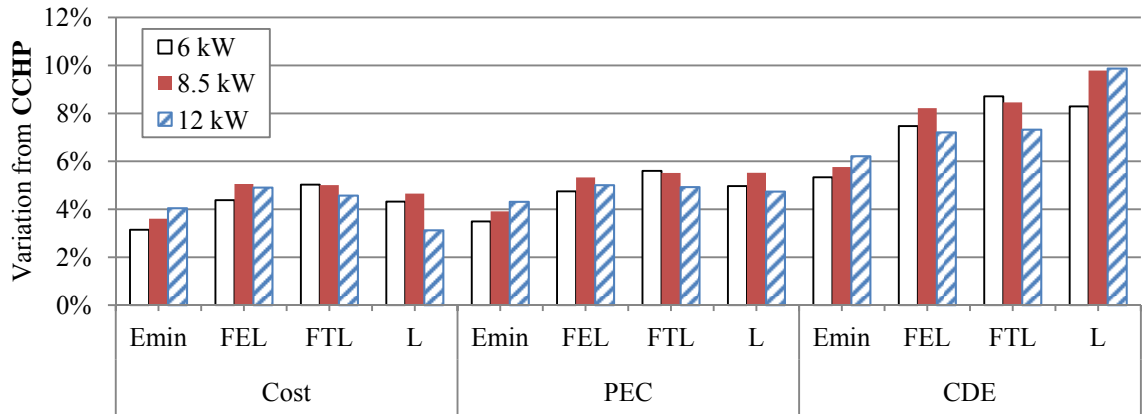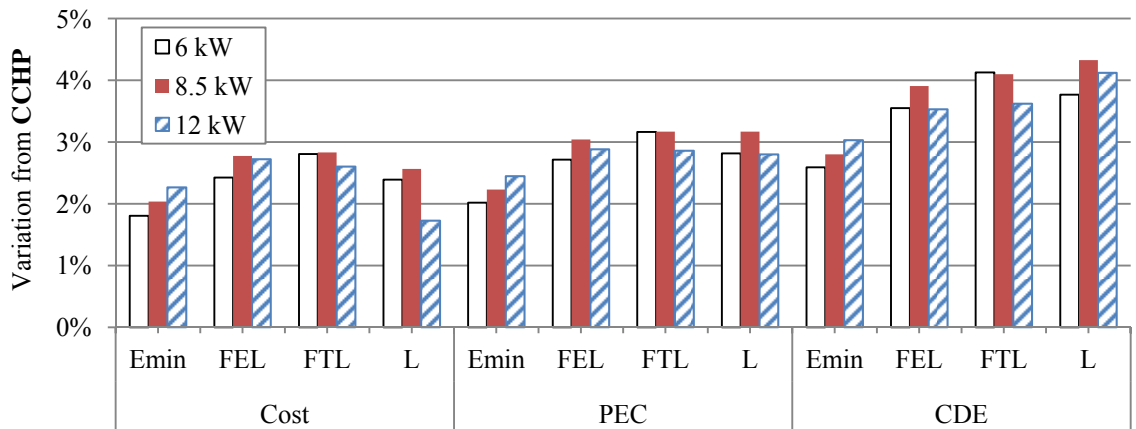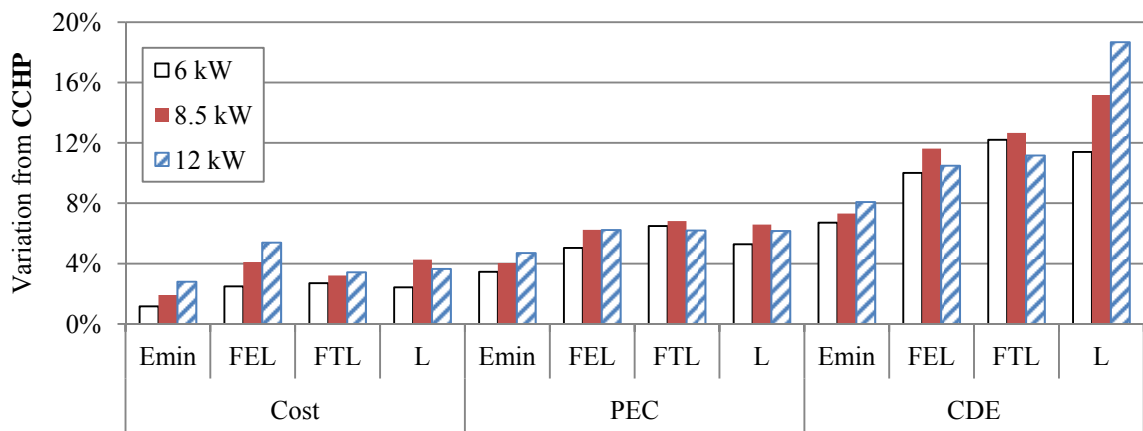
Figure 9.13   Performance of the CHP system with respect to the CCHP system while operating under continuous strategies in (a) Boulder, (b) Duluth, and (c) Chicago

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9.7   CHP System Optimization

As was the case for optimizing the CCHP system, optimizing the CHP system yields improvements over the non-optimized CHP system operating under the continuous strategies. In Boulder, Figure 9.14(a) illustrates that reductions over the reference case in cost, PEC, and CDE are obtainable during cost and PEC optimization. When compared to the CCHP system, Figure 9.14(b) demonstrates that even though the CDE optimized CHP system is worse than the equivalent CCHP system, the cost- and PEC-optimized CHP system are able to realize lower costs and lower PEC, but with higher emissions, when compared to the optimized CCHP system. With a cost- or PEC-optimized CHP system, Figure 9.13(a) demonstrates that the resulting costs, PEC, and CDE are now lower than the reference case, whereas for the optimized CCHP system, the cost and PEC were higher than the reference in all but the PEC for the 6-kW engine.

Figure 9.15 presents the case for the optimized CHP system in Duluth. During cost and PEC optimization, cost, PEC, and CDE are reduced from the reference case. In addition, the 6-kW CDE optimized CHP system is able to lower cost, PEC, and CDE below the levels of the reference case. Figure 9.15(b) illustrates that the optimized CHP system has lower costs, lower PEC, but higher emissions than the optimized CCHP system for all the optimization schemes.

Finally, according to Figure 9.16(a), optimizing the CHP system in Chicago reduces the PEC and CDE below the reference case for the cost and PEC optimization. However, the costs are still about 15% higher than the reference building. Figure 9.16(b) shows the cost- and PEC-optimized CHP system in Chicago is less costly to operate than the optimized CCHP system.

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(a)

(b)
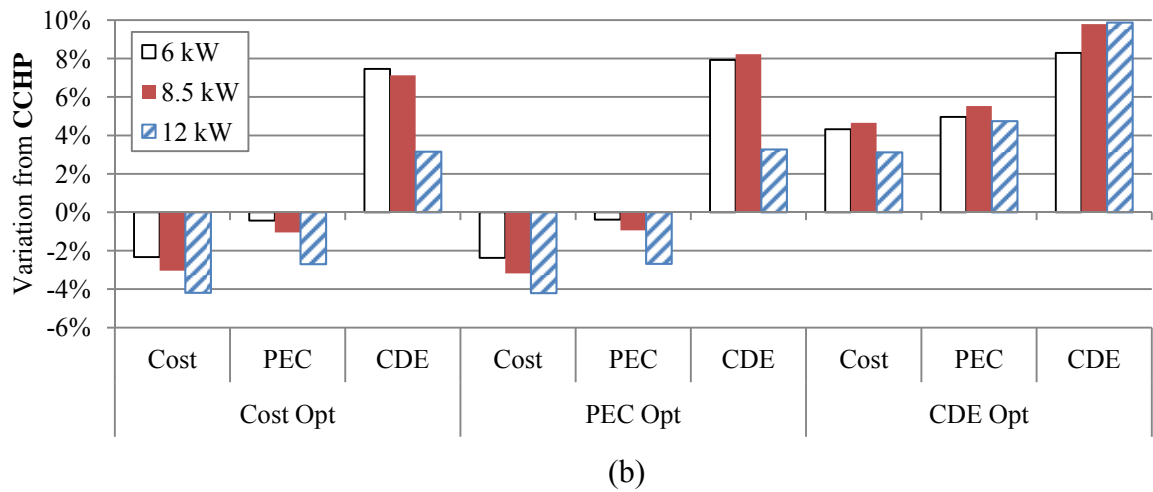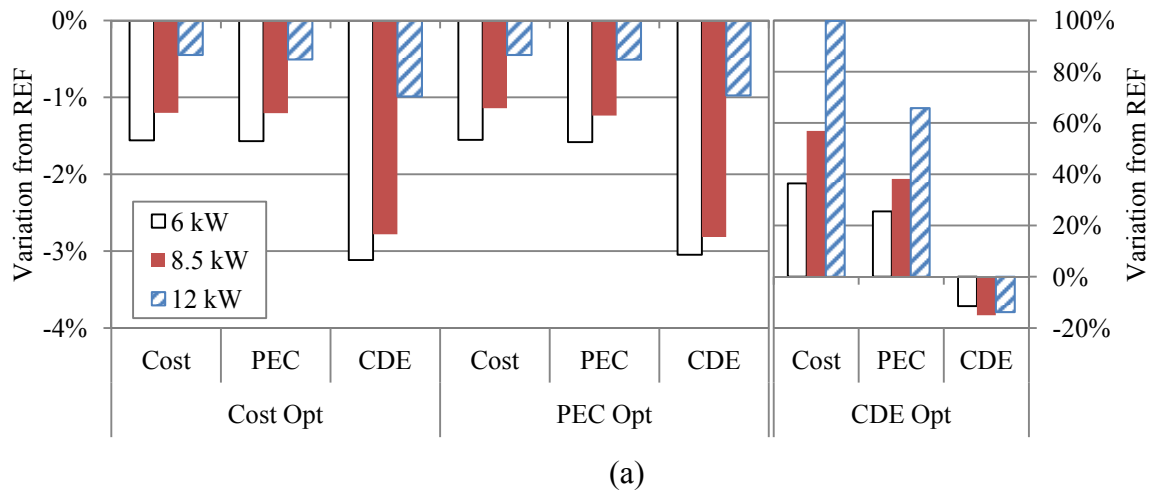
Figure 9.14   Performance of the CHP system optimized for cost, PEC, and CDE in Boulder versus (a) the reference case and (b) the optimized CCHP system
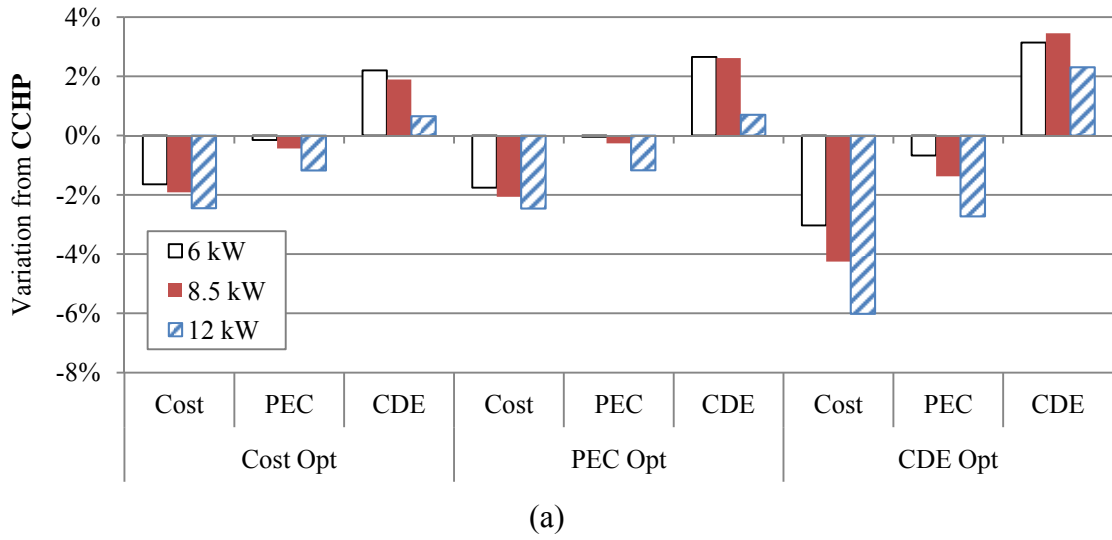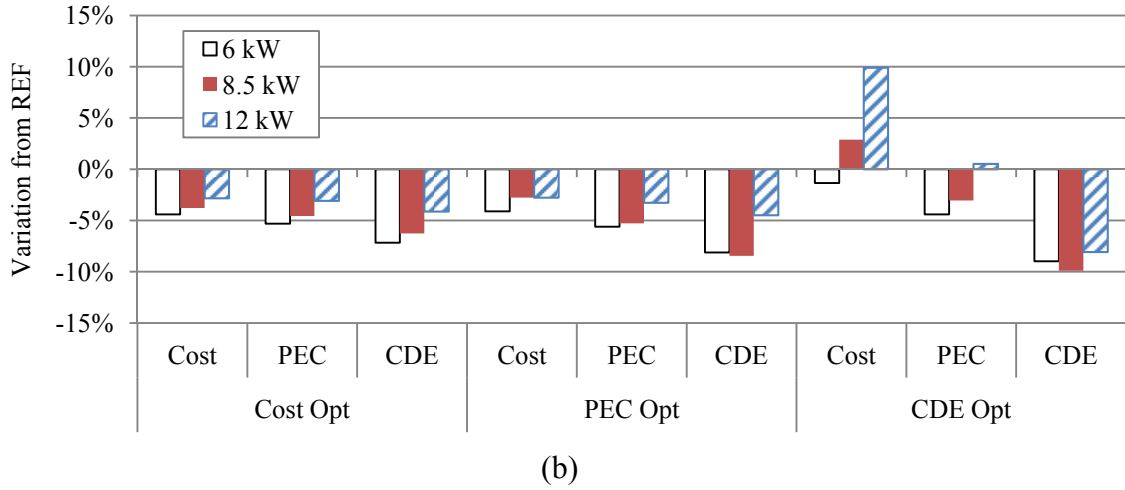
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Figure 9.15   Performance of the CHP system optimized for cost, PEC, and CDE in Duluth versus (a) the reference case and (b) the optimized CCHP system
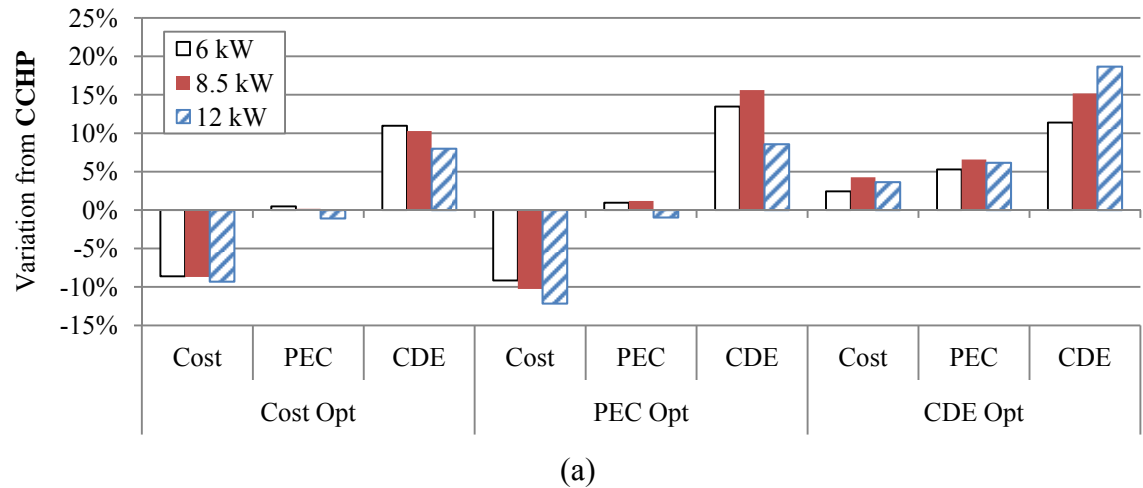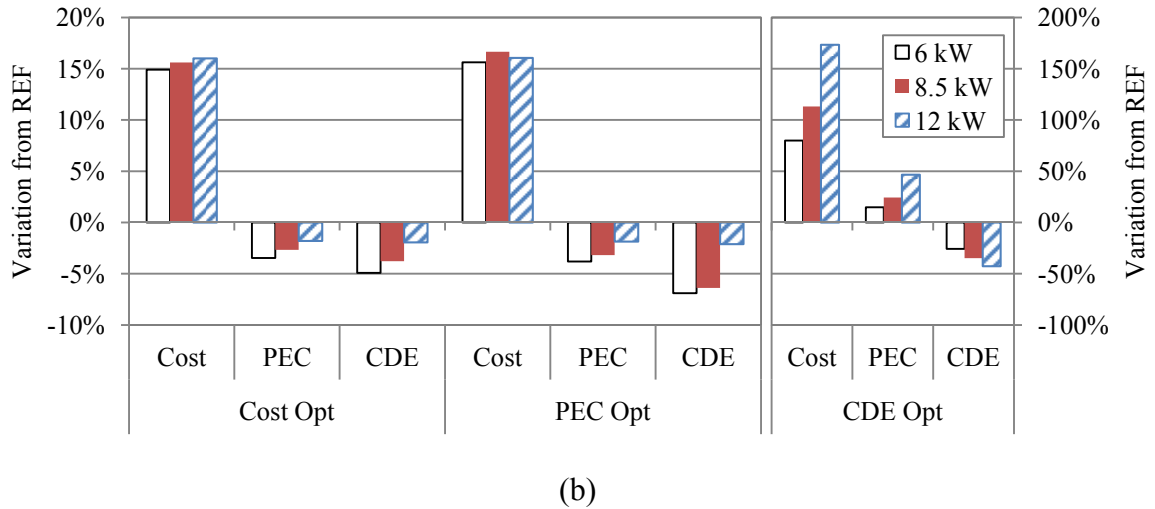
102

(b)

(a)

Figure 9.16   Performance of the CHP system optimized for cost, PEC, and CDE in Chicago versus (a) the reference case and (b) the optimized CCHP system

In conclusion, if operating the CHP or CCHP system continuously, the CCHP system is the preferred system because of its better waste heat utilization. However, operating the system continuously only makes sense if there is a large incentive to reduce carbon dioxide emissions. On the other hand, if operating the system to optimize the operational costs or PEC, a CHP system is generally preferred over a CCHP system.

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9.8   CHP System under Cutoff Strategies

Like the CCHP system, the FELc provided no benefits for the 6-kW engine and marginal benefits for the 8.5-kW and 12-kW engines. Figure 9.17 compares the FTL, FTLc, cost optimization, and PEC optimization results for the CHP system. Also like the CCHP system, the FTLc provides improvements over the FTL strategy and is comparable to the cost- and PEC-optimized results. In Boulder and Chicago, the cost and PEC of the FTLc strategy are within 1% of the optimized cases while in Duluth the cost and PEC of the FTLc strategy are within about 5% of the optimized cases. The CDE results have a slightly wider margin for the respective cities.

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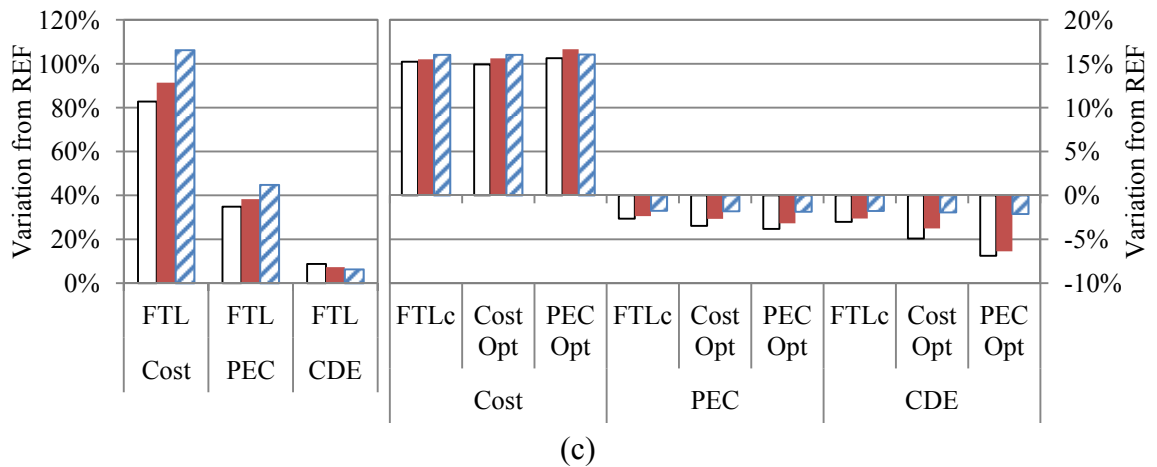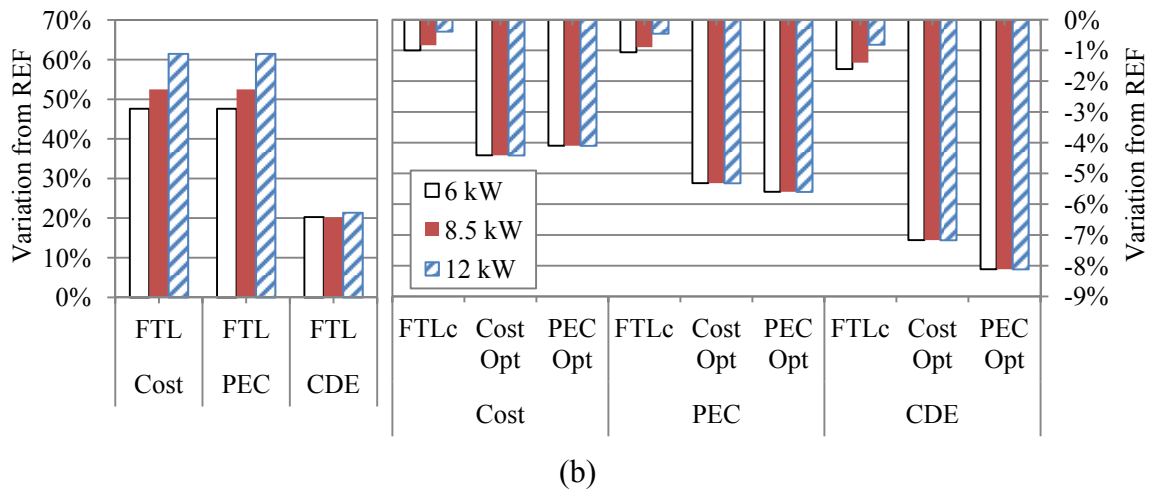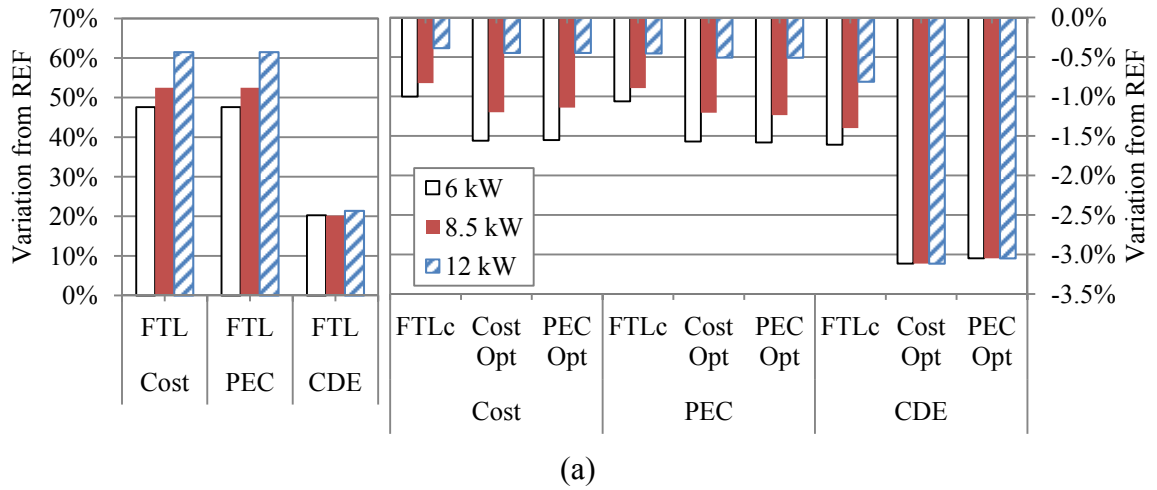
Figure 9.17   Comparison of FTL, FTLc, cost-optimized, and PEC-optimized CHP
system in (a) Boulder, (b) Duluth, and (c) Chicago

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CHAPTER 10

ANALYSIS AND OPTIMIZATION OF A CCHP-ORC SYSTEM AND A CHP-ORC

SYSTEM FOR A SMALL COMMERCIAL OFFICE BUILDING

This investigation extends Chapter 9 by combining an ORC with the previously studied CCHP and CHP systems.
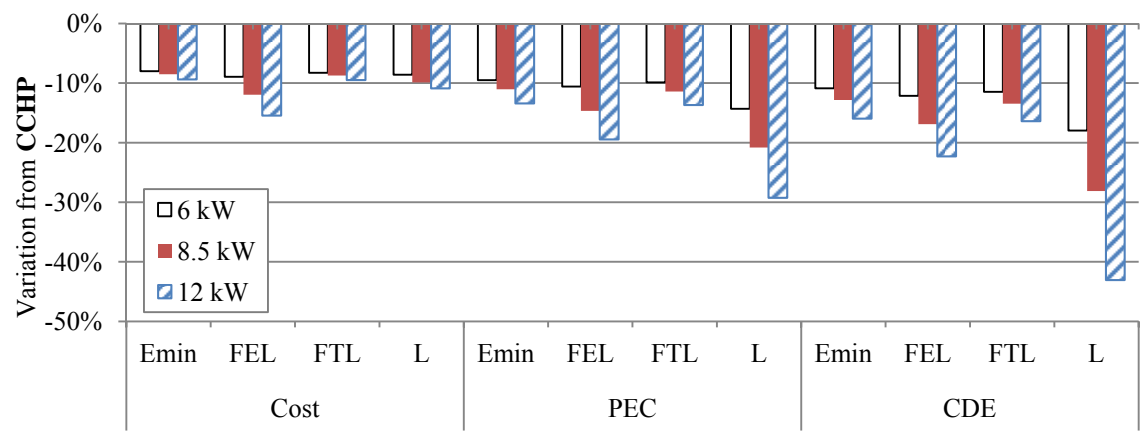
10.1   CCHP-ORC System

While operating under the continuous strategies, Figure 10.1 compares the CCHP-ORC performance to the independent CCHP system evaluated in Chapter 9CHAPTER 9. Cost, PEC, and CDE results are presented for the 6-kW, 8.5-kW, and 12-kW engines in the cities of Boulder, Duluth, and Chicago. Operating the CCHP-ORC system under the continuous operational strategies is able to provide improvements from an independent CCHP system in terms of cost, PEC, and CDE. This is because (1) the ORC is able to convert any extra heat to additional power without the expense of consuming additional fuel and (2) operating the system continuously under the continuous strategies generates excess heat. The larger the engine size will have the most excess heat and, therefore, yield larger improvements over the stand-alone CCHP system. This also holds true for the FEL and L strategies. In Duluth, combining an ORC with a FEL operated CCHP system yields cost savings of 8.9%, 12.0%, and 15.4% for the 6-kW, 8.5-kW, and 12-kW

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engines. In addition, comparing the results for the different cities in Figure 10.1 shows nearly identical trends.

Even though the CCHP-ORC system is an improvement over a standalone CCHP system, Figure 10.2 indicates that for all the operational strategies, the cost is still above those for the reference case. In addition, the PEC for E_{min}, FEL, and FTL strategies are higher than the reference case. In terms of PEC, the best performing operational strategy for the 12-kW engine shifts from the FTL strategy for the CCHP system, see Table 9.8, to full-load operation for the CCHP-ORC system. Moreover, FEL is now the best performing cost strategy or within 1% of the best performing cost strategy for all the engines in every cities. Concerning engine size, like the CCHP system operation, decreasing the engine size in the CCHP-ORC system generally reduces the cost and PEC, but unlike operation of the CCHP system, a more defined trend in emissions is present for the CCHP-ORC system where increasing the engine size decreases CDE.
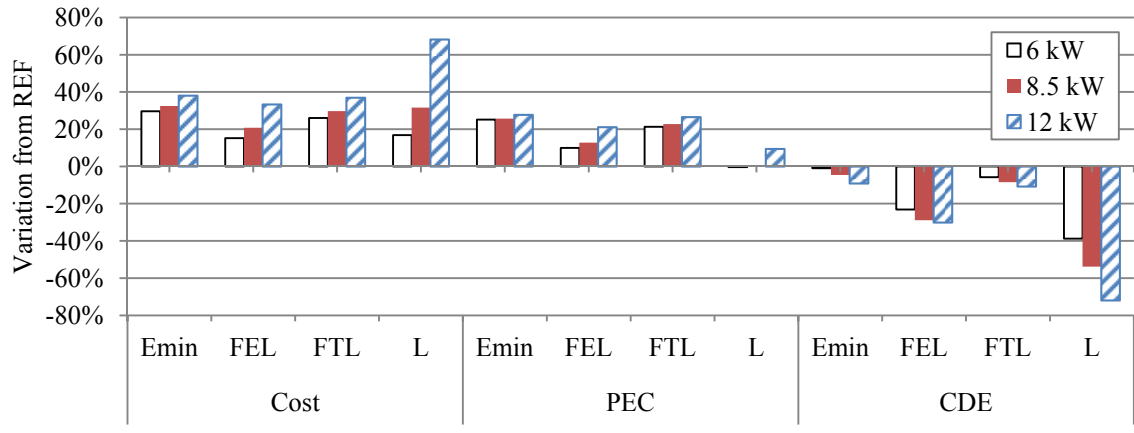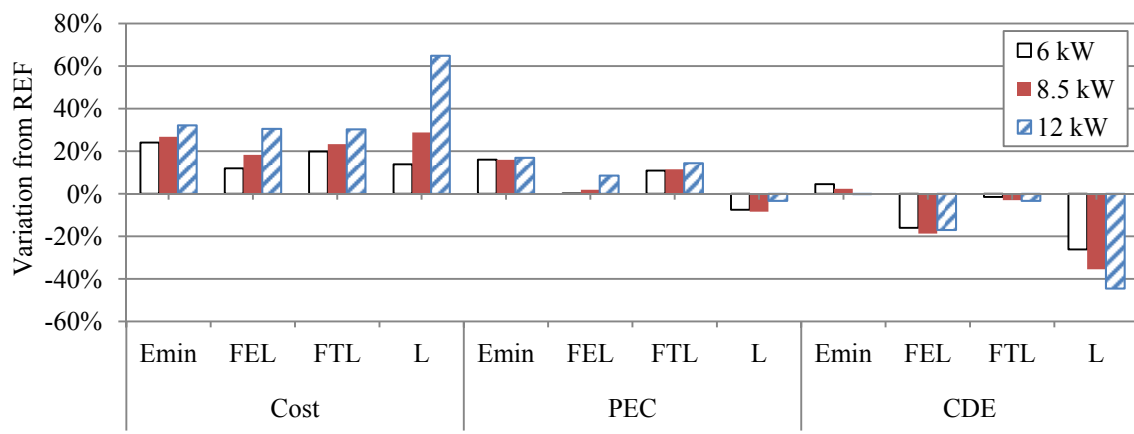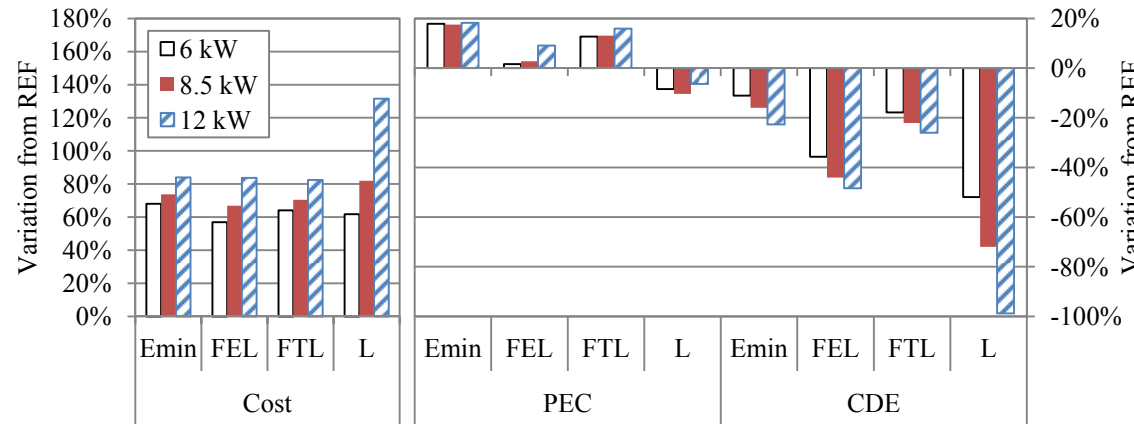
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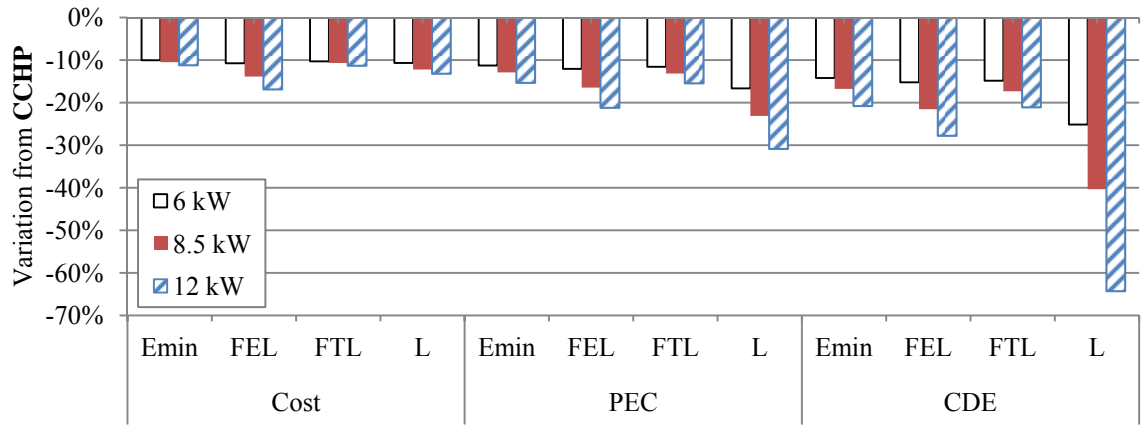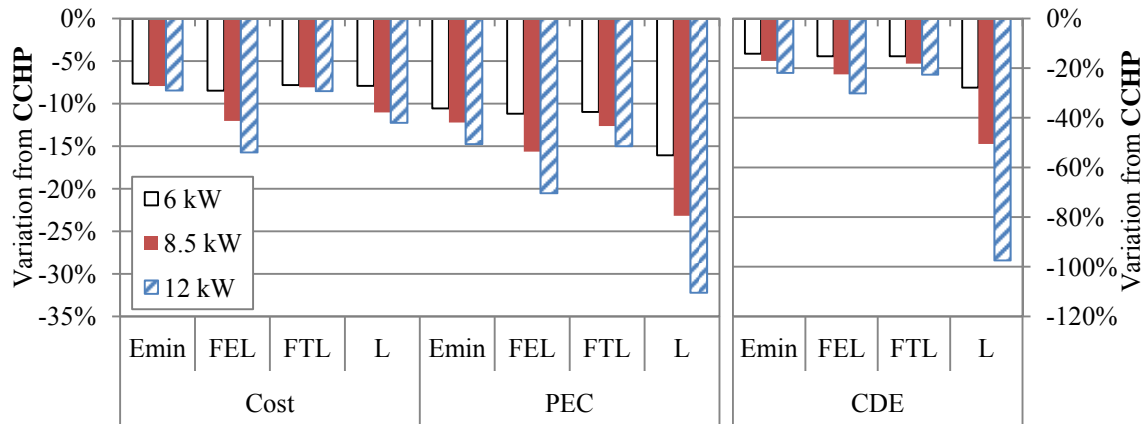
Figure 10.1   CCHP-ORC system performance versus the CCHP system under continuous operational strategies in (a) Boulder, (b) Duluth, and (c) Chicago

108

(a)

(b)

(c)

Figure 10.2   CCHP-ORC system performance versus the reference case under
continuous operational strategies in (a) Boulder, (b) Duluth, and (c)
Chicago

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With respect to the reference case, Figure 10.3 displays the cost, PEC, and CDE results for the optimized CCHP-ORC system. These results are an improvement over the non-optimized CCHP-ORC system results given in Figure 10.2. For the city of Boulder, Figure 10.3(a), cost optimizing the 6-kW and 8-kW engines or optimizing the PEC for the 6-kW engine will reduce the cost, PEC, and CDE from the reference case which were not possible for the optimized CCHP system, Figure 9.4(a).

Figure 10.4 compares the performance of the optimized CCHP-ORC system to the optimized CCHP system. It demonstrates that the optimization criterion is always lower for the CCHP-ORC system, but in some cases this comes at the expense of the other performance metrics. The CDE optimization of the CCHP-ORC system in Duluth, for example, lowers the CDE over the CDE-optimized CCHP system, but this comes at the expense of higher costs. Similarly, PEC optimization of the CCHP-ORC in Chicago yields lower PEC but higher costs than the PEC-optimized CCHP system. In Chicago, cost optimizing the CCHP-ORC system does not provide any improvement over the cost-optimized CCHP system because the system chooses to FTL or to turn the engine off.

In Chicago, the costs are over 50% higher than the reference case, which is not practical. The only possible operating strategy in Chicago would be to minimize costs, which still produces costs that are at least 20% higher than the reference case. However, for this strategy, the addition of an ORC to the CCHP system does not provide any benefits. In Boulder and Duluth, the addition of an ORC improves the CCHP system and also provides performance that is better than the reference building during some of the optimized cases.
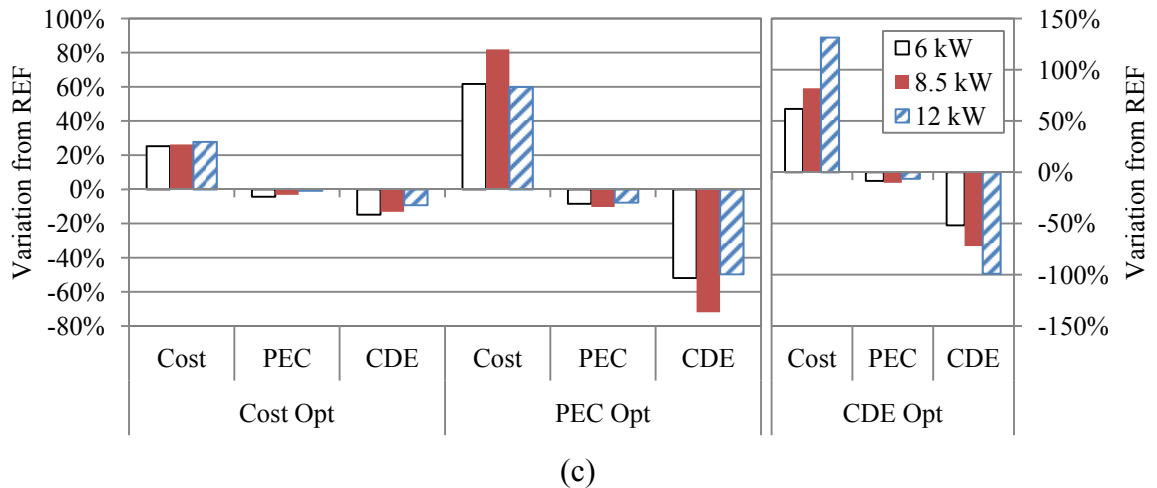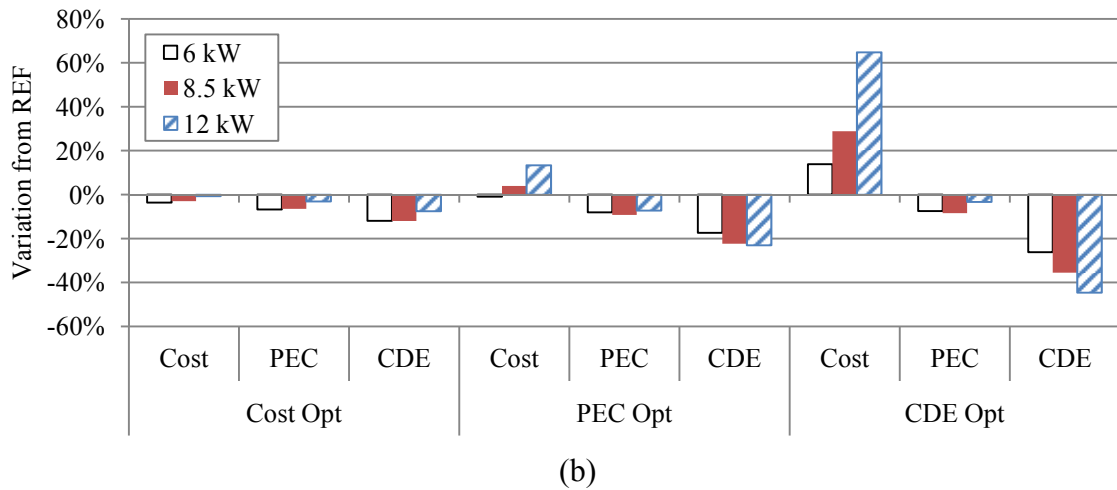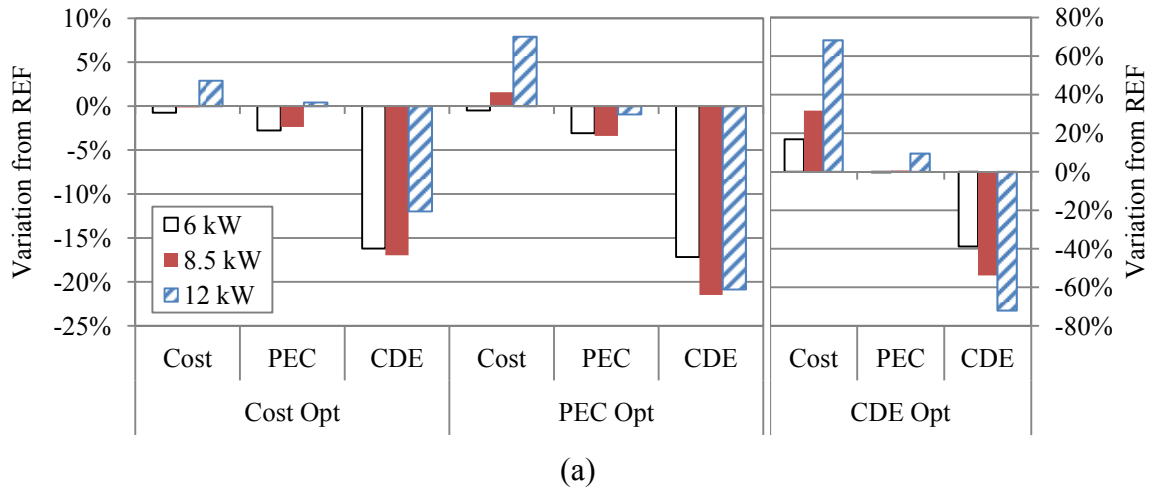
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(a)

(b)

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Figure 10.3   Optimized CCHP-ORC system performance versus the reference case in
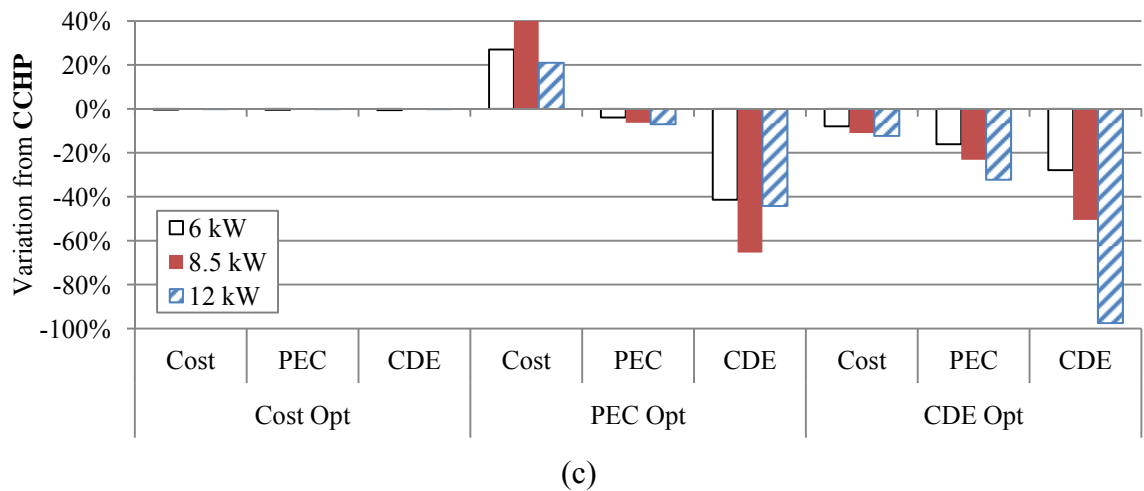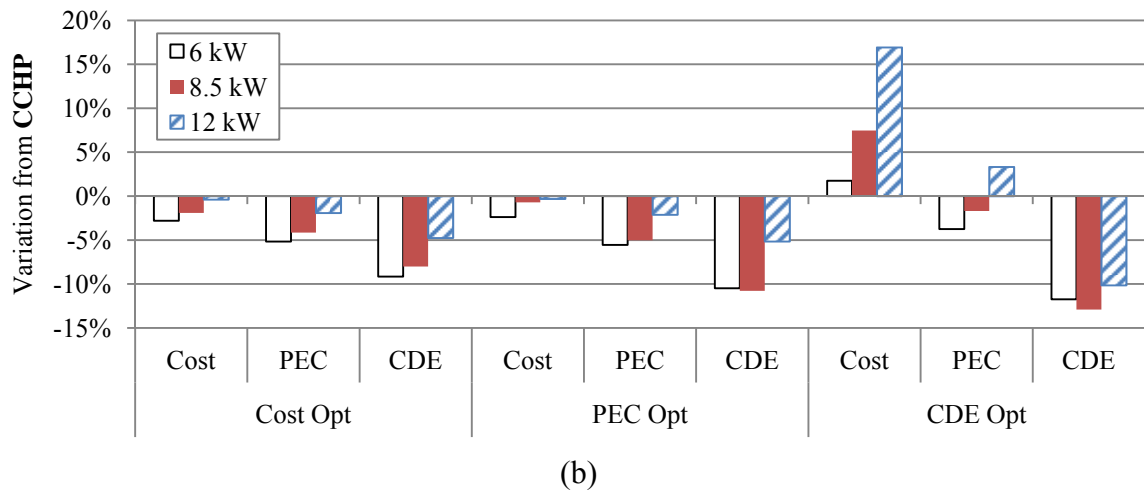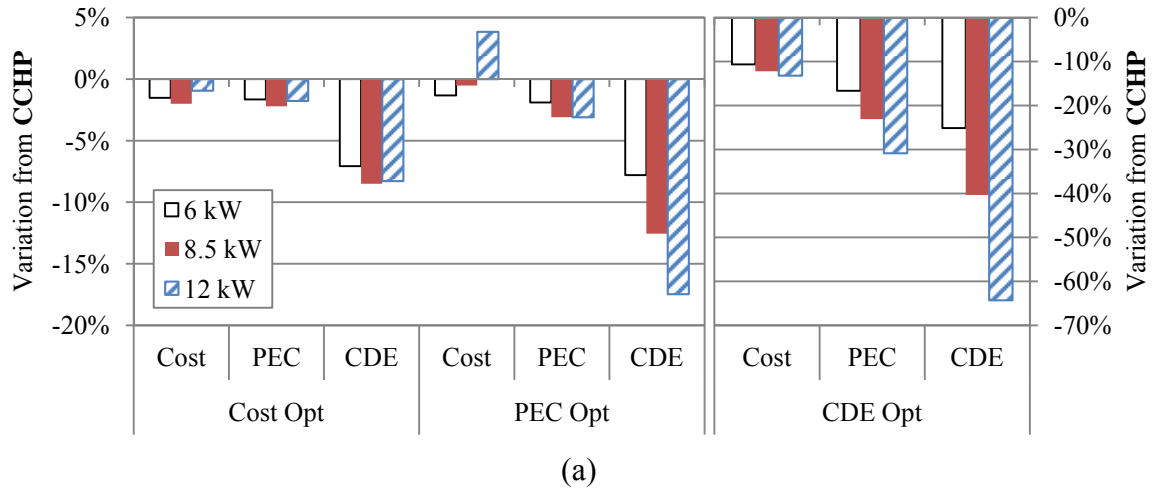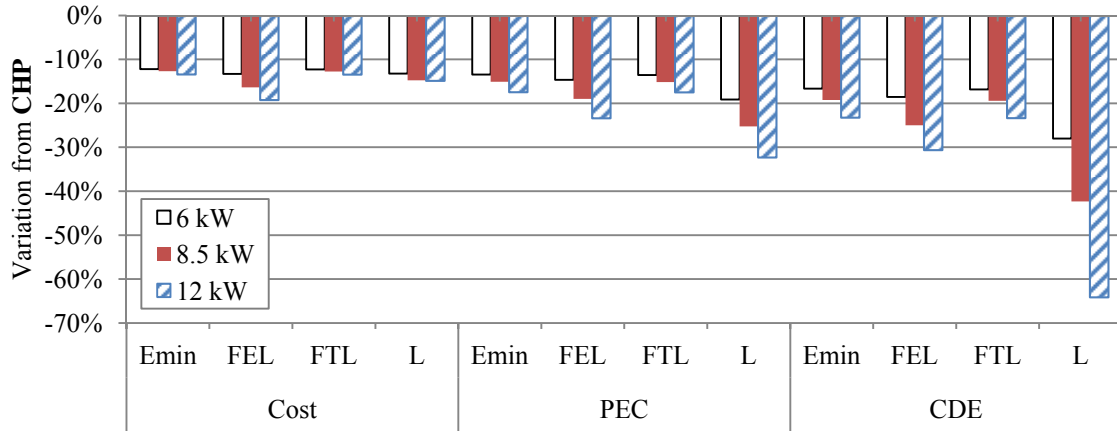(a) Boulder, (b) Duluth, and (c) Chicago

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Figure 10.4   Optimized CCHP-ORC system performance versus the optimized CCHP
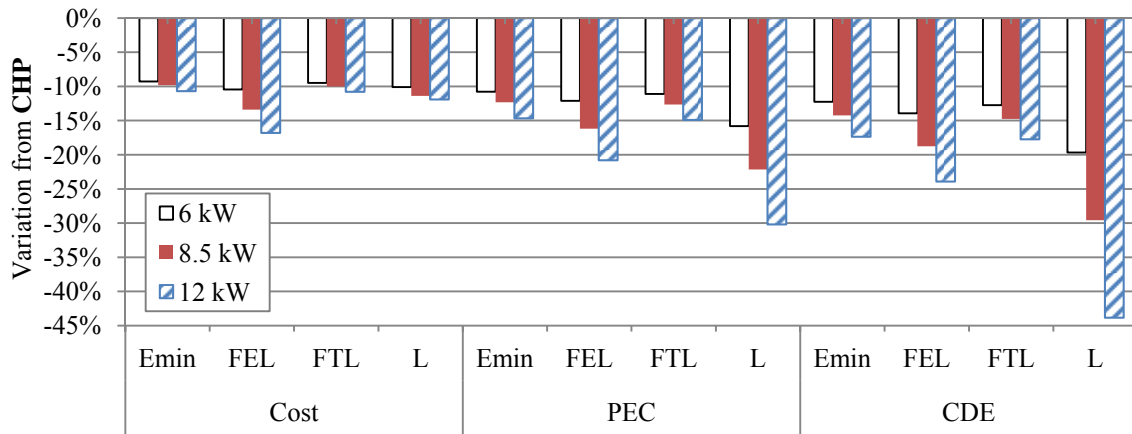system in (a) Boulder, (b) Duluth, and (c) Chicago

10.2 CHP-ORC System

As was the case for the CCHP-ORC system, Figure 10.5 validates that for the continuous strategies, the addition of an ORC to a CHP system reduces the cost, PEC, and CDE from the values of the standalone CHP system. Although, Figure 10.6 confirms that the cost for all the continuous operation strategies and the PEC of the E_{min}, FEL, and FTL strategies is still higher than the reference case. Similar to the case for the CHP system performance versus the CCHP performance, Figure 10.7 indicates that the performance of the CHP-ORC system is generally worse than the CCHP-ORC system for the continuous operational strategies. There are exceptions in Chicago, where the cost of the CHP-ORC with a 6-kW engine operating E_{min}, FEL, and L along with the 8.5-kW engine operating under E_{min} are slightly better than the CCHP-ORC system.
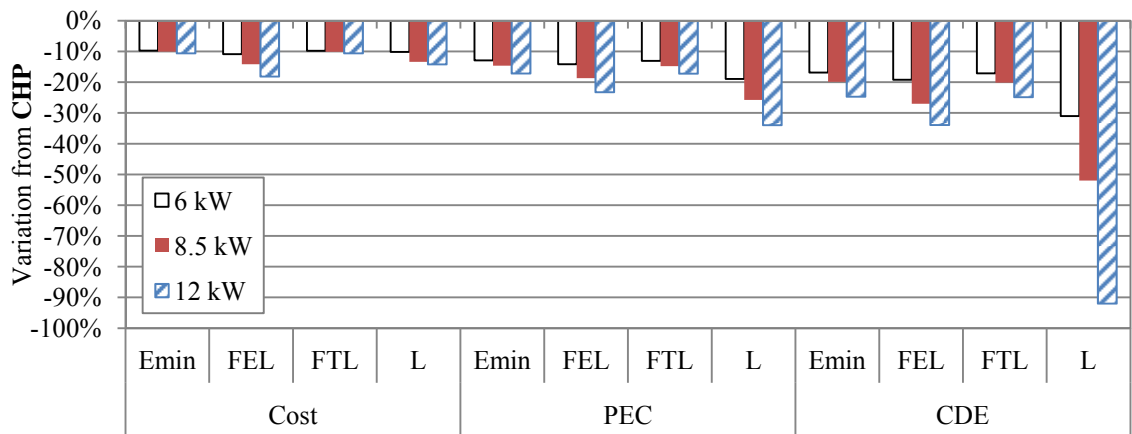
Under continuous operation, a CCHP system will perform better than a CHP system operating under the same strategy because the CCHP system is able to utilize more waste heat during the summer months for cooling the building. This leaves less surplus heat for an ORC cycle than would be available for an ORC cycle combined with a CHP system. Therefore, the use of ORC to recover the unused exhaust heat would be more beneficial to a CHP system. Nevertheless, a CCHP-ORC system would still be superior to a CHP-ORC system, if the systems run continuously.

113

(a)

(b)

(c)

Figure 10.5   CHP-ORC system performance versus CHP system for the continuous operational strategies in (a) Boulder, (b) Duluth, and (c) Chicago

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Figure 10.6   CHP-ORC system performance versus the reference case for the continuous operational strategies in (a) Boulder, (b) Duluth, and (c) Chicago

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Figure 10.7   CHP-ORC system performance versus CCHP-ORC system for the continuous operational strategies in (a) Boulder, (b) Duluth, and (c) Chicago
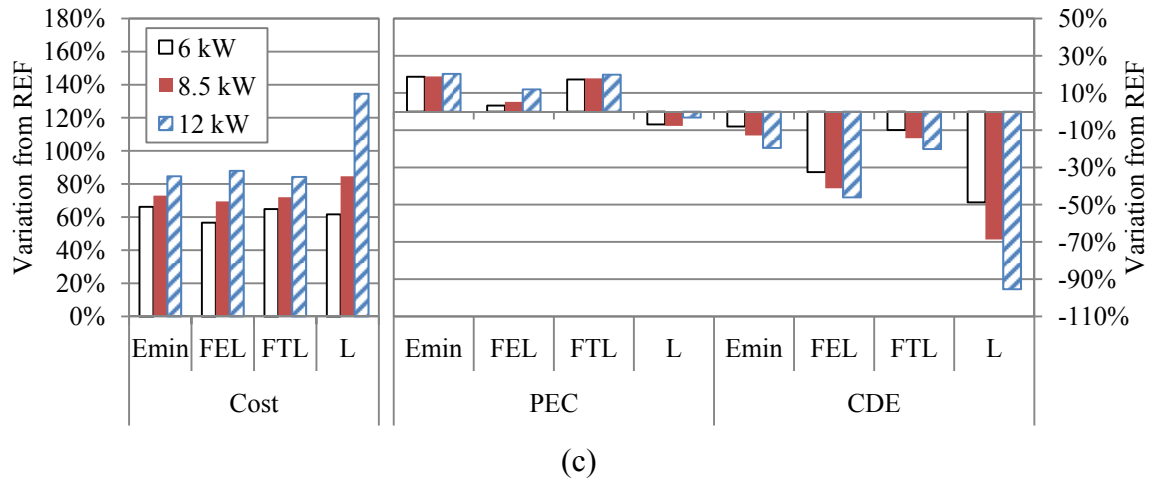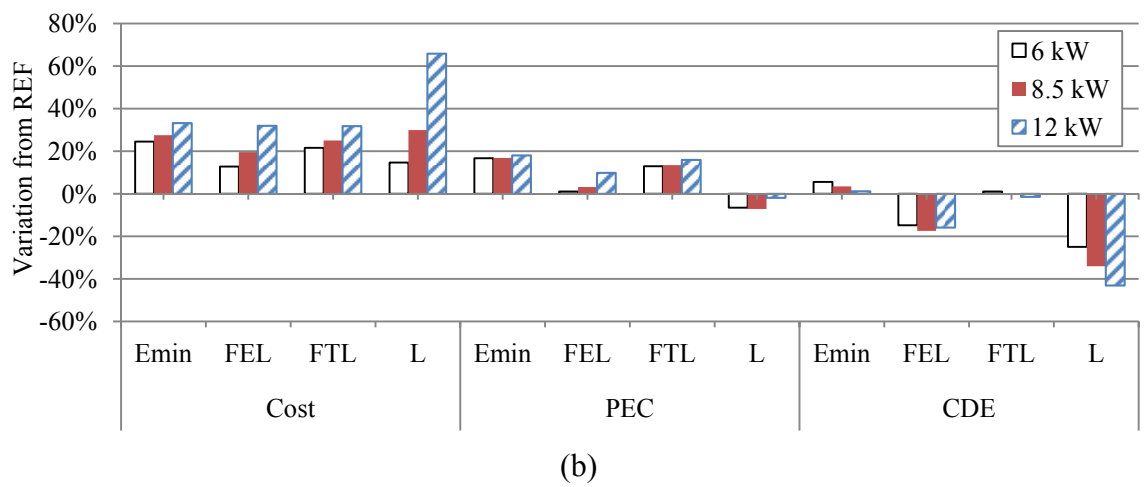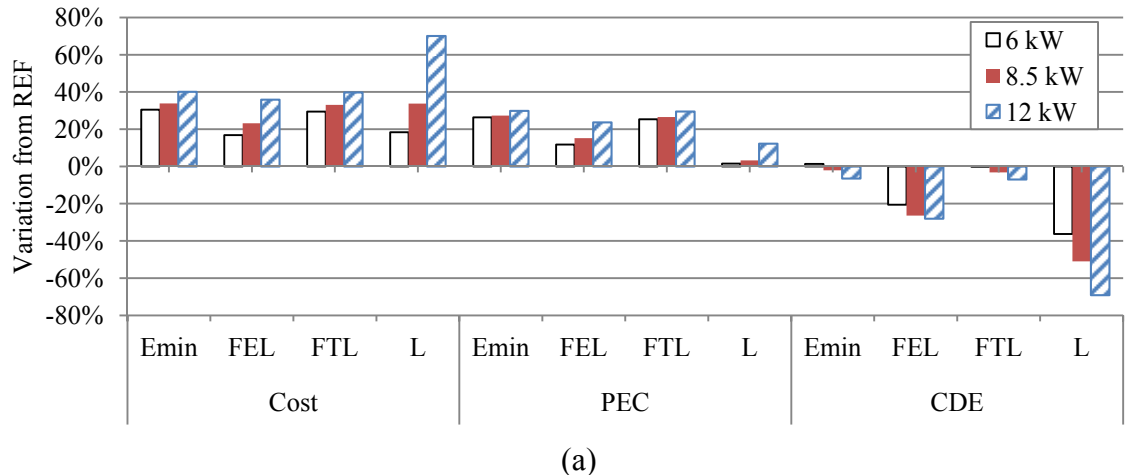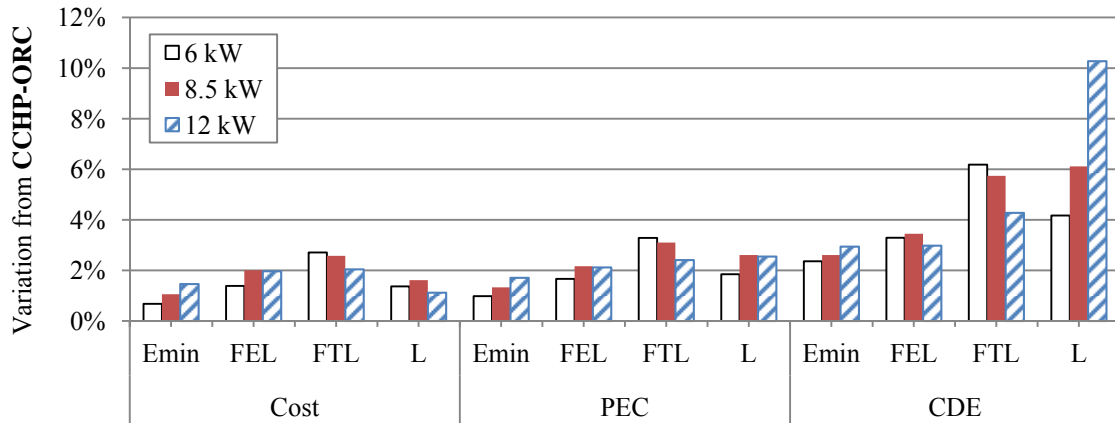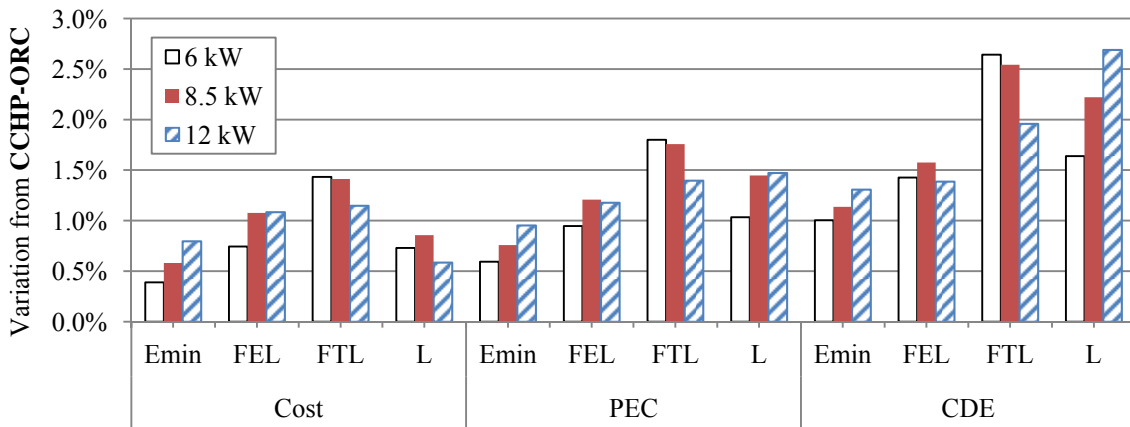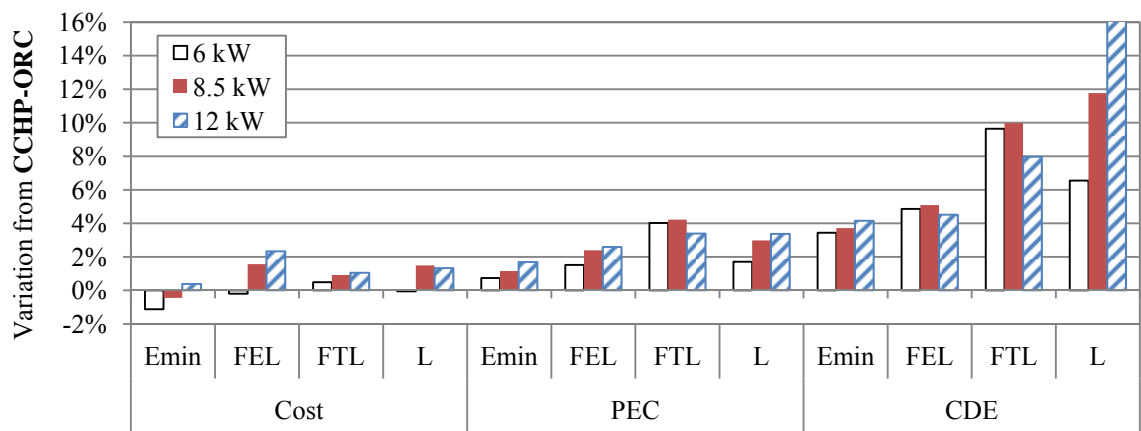
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With respect to the reference case, Figure 10.8 presents the results from optimizing the CHP-ORC system. Comparing Figure 10.8 to the results of the non-optimized CHP-ORC system of Figure 10.6 demonstrates that optimizing the system in terms of cost or PEC yields dramatic improvements in cost, PEC, and CDE performance. However, CDE optimization does not improve the performance from full-load operation.

Figure 10.9 gives the performance of the optimized CHP-ORC system with respect to the optimized CHP system. The relationship between the CHP-ORC and CHP system is generally the same as the relationship between the CCHP-ORC and CCHP system where the addition of an ORC under the optimized strategies improves the performance of the optimization criterion but a tradeoff may exists with the cost.

When comparing the optimized CHP-ORC system to the optimized CCHP-ORC system, Figure 10.10, the CHP-ORC system provides the lowest cost during the cost-optimized strategy but this comes at the expense of higher emissions and for the 6-kW and 8-kW engines higher PEC. The best PEC results during PEC optimization comes from the CHP-ORC system for the 6-kW and 8-kW engines but will also have higher costs, and the CCHP-ORC system gives the lowest PEC results for the 12-kW engine but has higher emissions. During CDE-optimization, the CCHP-ORC system produces the lowest emissions, which is accompanied by lower costs and lower primary energy consumption. Therefore, the choice between an optimized CCHP-ORC system and an optimized CHP-ORC system will depend on the priorities of the operator and engine size.
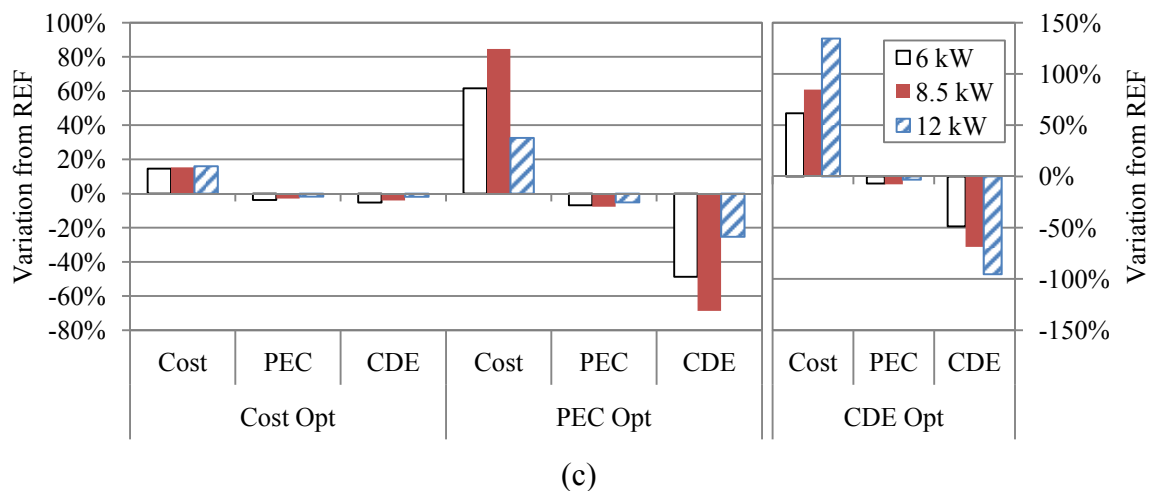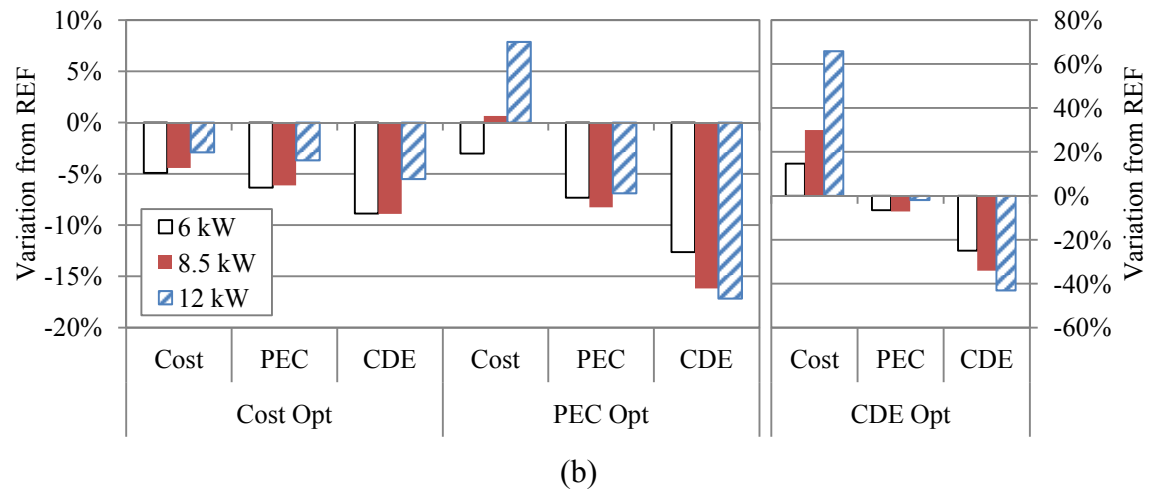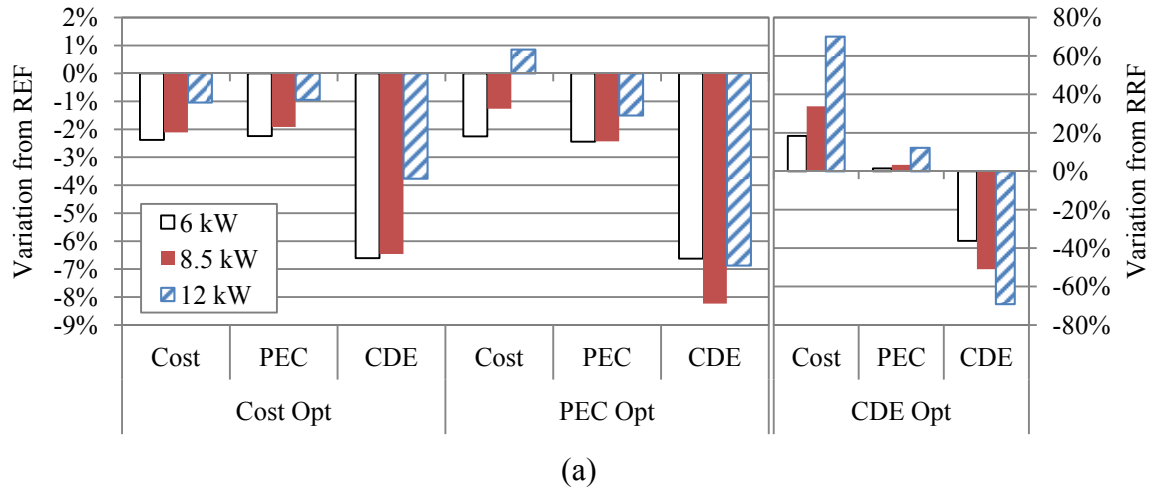
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Figure 10.8   Optimized CHP-ORC system versus the reference case in (a) Boulder, (b) Duluth, and (c) Chicago

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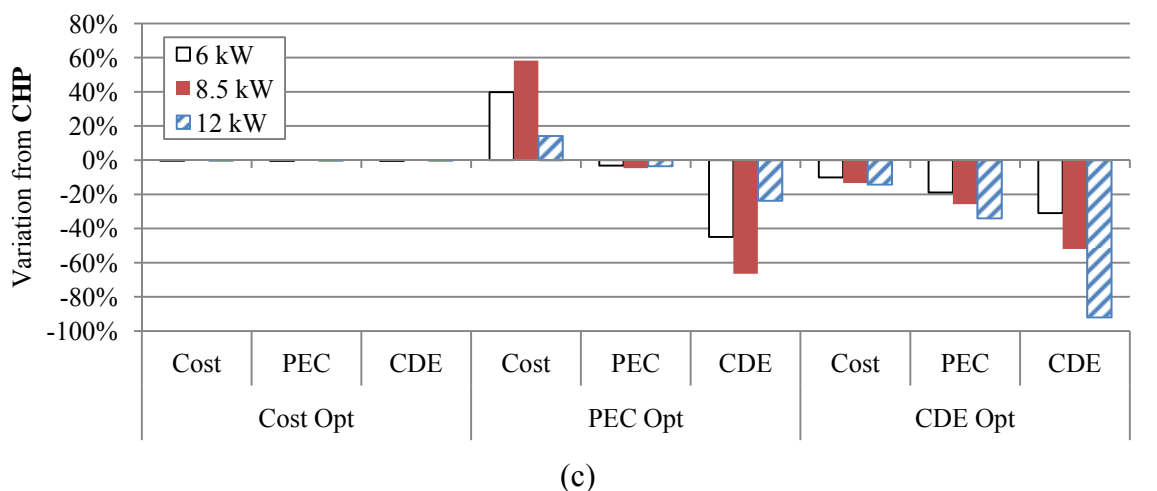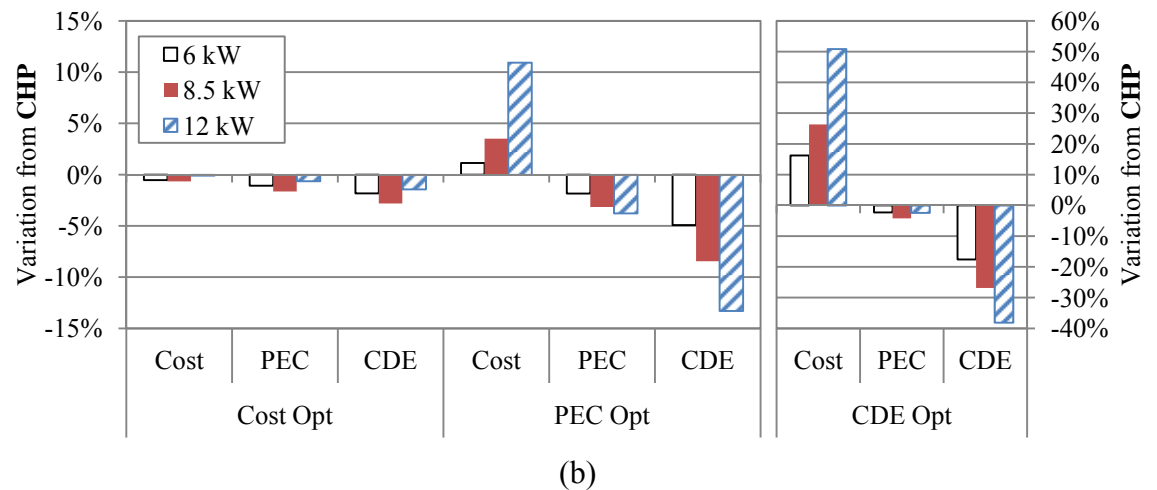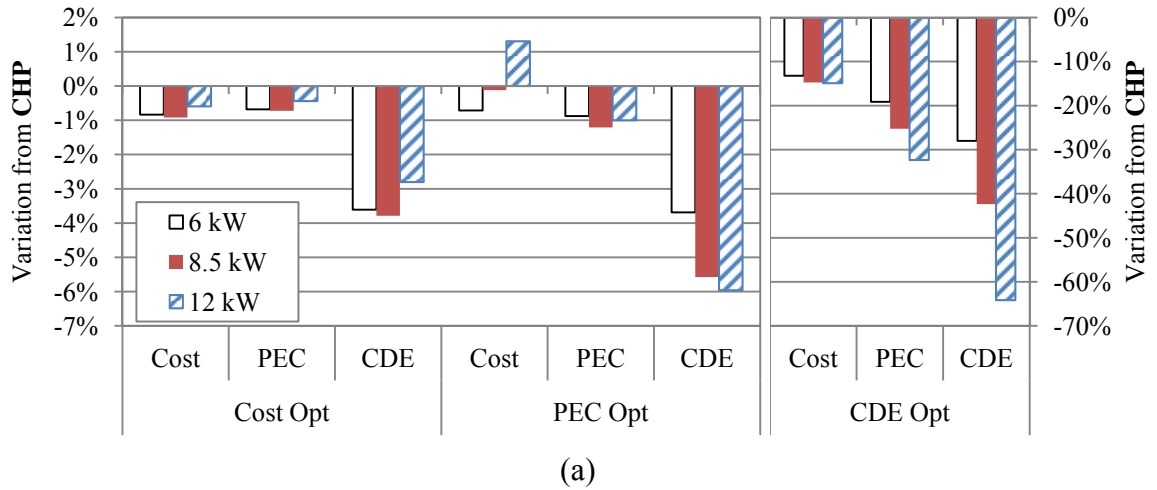
Figure 10.9   Optimized CHP-ORC system performance versus the CHP system in (a)
Boulder, (b) Duluth, and (c) Chicago

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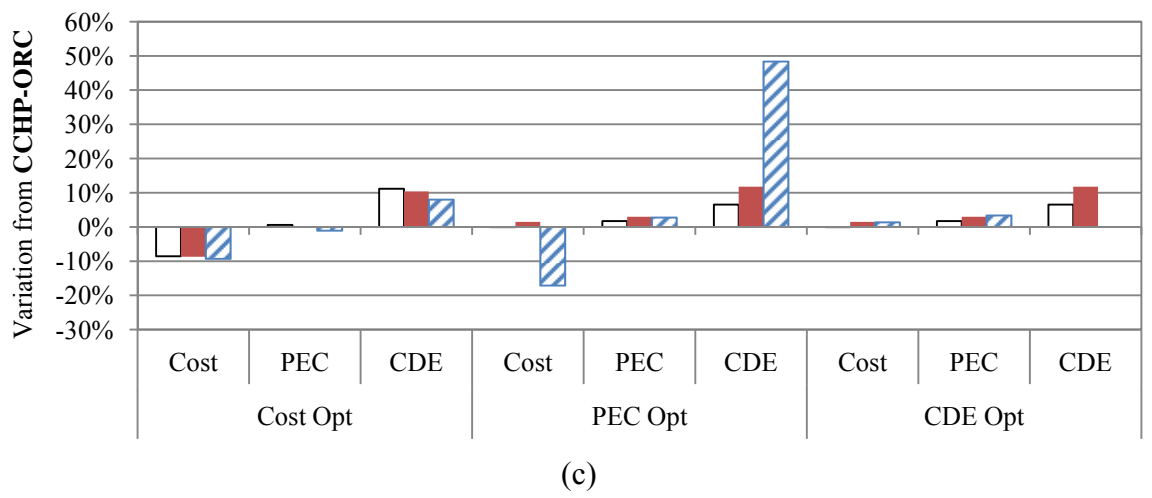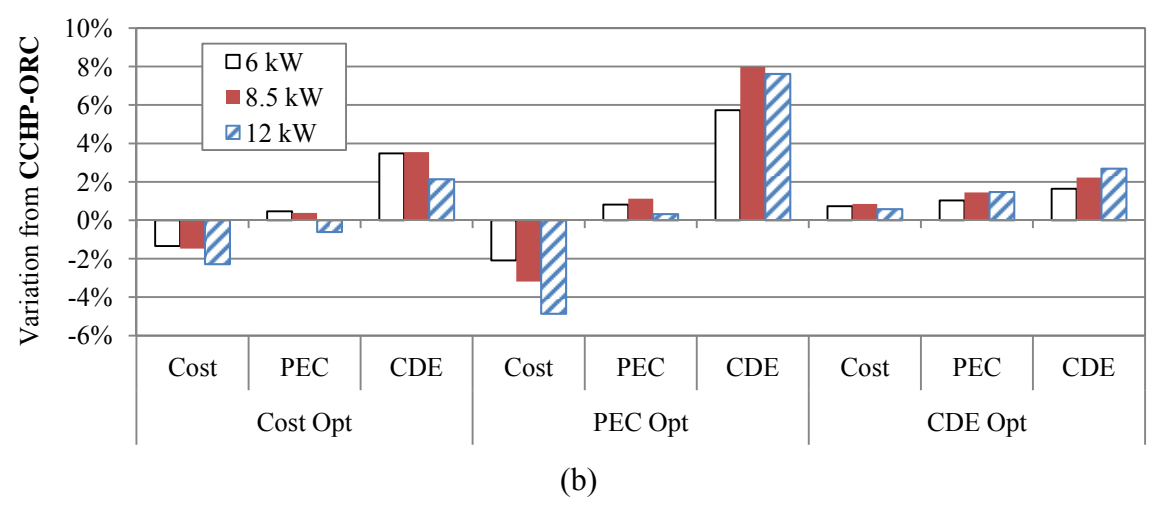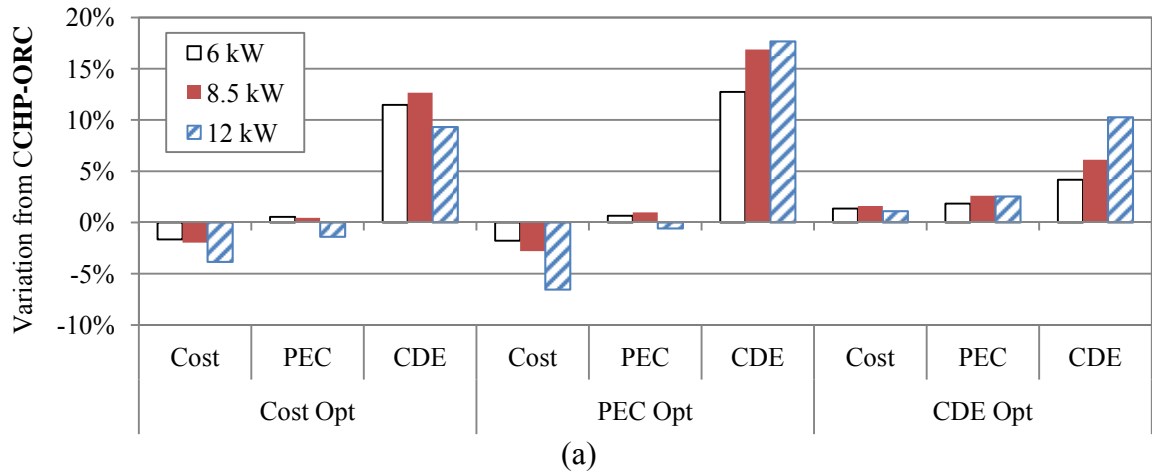
Figure 10.10   Optimized CHP-ORC system versus the optimized CCHP-ORC system in (a) Boulder, (b) Duluth, and (c) Chicago

CHAPTER 11

EVALUATION OF A TURBINE DRIVEN CCHP SYSTEM FOR A LARGE OFFICE

BUILDING UNDER DIFFERENT OPERATING STRATEGIES

For a large office building located in Chicago, IL, a CCHP system was simulated using FEL, FTL, and FSS operational strategies. For the various strategies, the distribution of total carbon dioxide emissions by source is presented. This study explores the use of carbon credits to establish how the reduction in carbon dioxide emissions that is possible from operation of the CCHP system could translate into economic benefits. In addition, the capital costs available for the CCHP system are determined using the simple payback period. Table 11.1 presents the values of the variables used to model the CCHP system, while Table 11.2 presents the characteristics of the PGU, which uses a load-share turbine for power generation. For Chicago, the utility rate structure for the large office building is given in Table 11.3, while the PEC and CDE emissions factors are presented in Table 11.4.

Table 11.1   CCHP system parameters

Parameter	Value
Boiler efficiency coeficient[*], A	-448×10^{-4}
Boiler efficiency coeficient[*], B	93×10^{-4}
Boiler efficiency coeficient[*], C	0.8555
Heat recovery system efficiency, η_{rec}	0.80
Heating coil efficiency, η_{hc}	0.88
Chiller coefficient of performance, COP_{ch}	0.70

[*] ASHRAE Handbook [38]

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Table 11.2   PGU characteristics for the load-share turbine

Parameter	Value
Max PGU load, L (kW)	800
Max PGU efficiency, η_{pgu}	0.33
Min PGU load (%)	6.5
Min PGU load, E_{min} (kW)	52
PGU coefficient[*], a	-813.33×10^{-10}
PGU coefficient[*], b	427.99×10^{-07}
PGU coefficient[*], c	-839.67×10^{-05}
PGU coefficient[*], d	783.00×10^{-03}
PGU coefficient[*], e	-433.72×10^{-13}
PGU coefficient[*], a′	-119.99×10^{-6}
PGU coefficient[*], b′	971.93×10^{-4}
PGU coefficient[*], c′	13.2915
PGU coefficient[*], a″	-326.50×10^{-7}
PGU coefficient[*], b″	477.36×10^{-4}
PGU coefficient[*], c″	16.1135
PGU coefficient[*], a‴	-931.3×10^{-8}
PGU coefficient[*], b‴	232.87×10^{-4}
PGU coefficient[*], c‴	20.3465

[*]Capstone [37]

Table 11.3   Chicago cost data for the large office building [35]

	A		B	
	Size (kWh)	Cost ($/kWh)	Size per Demand	Cost ($/kW)
Block 1	300	0.082409	190	0
Block 2	700	0.072873	110	0.051773
Block 3	1500	0.061696	remaining	0.046965
Block 4	remaining	0.041179		
Energy Charge, r_e ($/kWh)	0.00435			
Monthly Charge ($)	9.4			
Taxes, t (%)	8			

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Table 11.4　　　PEC and CDE factors for Chicago [42]

| | PEC Factor (kWh/kWh) | CDE Factor (kg/kWh) | CDE Factor Precomb (kg/kWh) | CDE Factor on-site (kg/kWh) | |
				PGU – small turbine	Commercial boiler
Electricity	3.546	1.23	-	-	-
Natural Gas	1.092	-	0.017460	0.183492	0.183492

Figure 11.1 gives the annual operational cost (not including carbon credits), PEC, and CDE for the evaluated strategies as the percent variation from the reference case. With respect to the reference case, all the evaluated operational strategies reduce the cost, PEC, and CDE. The highest reduction in cost from the reference case is a result of the FTL with export strategy (3.6%), which is just slightly better that the cost reduction for FTL without export (3.5%). Regarding PEC, FSS operation yields the maximum PEC reduction from the reference case (15.1%) while the minimum reduction occurs during FTL without export (7.3%). FTL with export and FEL yielded a reduction of 14.2% and 13.1%, respectively. The CDE reductions for FEL, FSS, FTL with export, and FTL without export were 48.3%, 47.3%, 36.5%, and 29.2%, respectively. This figure illustrates that for the evaluated large office building, one of the biggest advantages of utilizing CCHP systems is the significant reduction of CDE.

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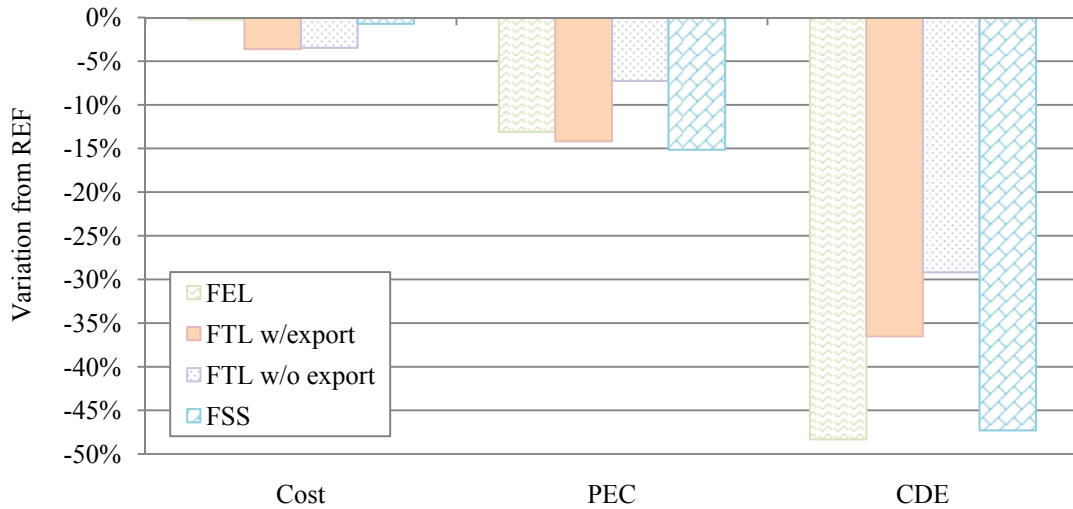
Figure 11.1   Percent variation from the reference case of the cost, PEC, and CDE for the CCHP system under the different operational strategies

As mentioned before, the FSS strategy obtained the maximum PEC reduction. Figure 11.2 explains this by plotting the monthly PEC for three different evaluated operational strategies. This figure illustrates how the FSS strategy follows the electric load for some months and follows the thermal load for the remaining months. For the months of February, March, April, May, September, October, and November, LF>1; therefore, the CCHP system follows the electric load. For the other months, LF<1, and the system follows the thermal load. For each month, the FSS strategy essentially follows the FEL or FTL strategy that consumes less primary energy, which evidently will reduce the annual PEC.

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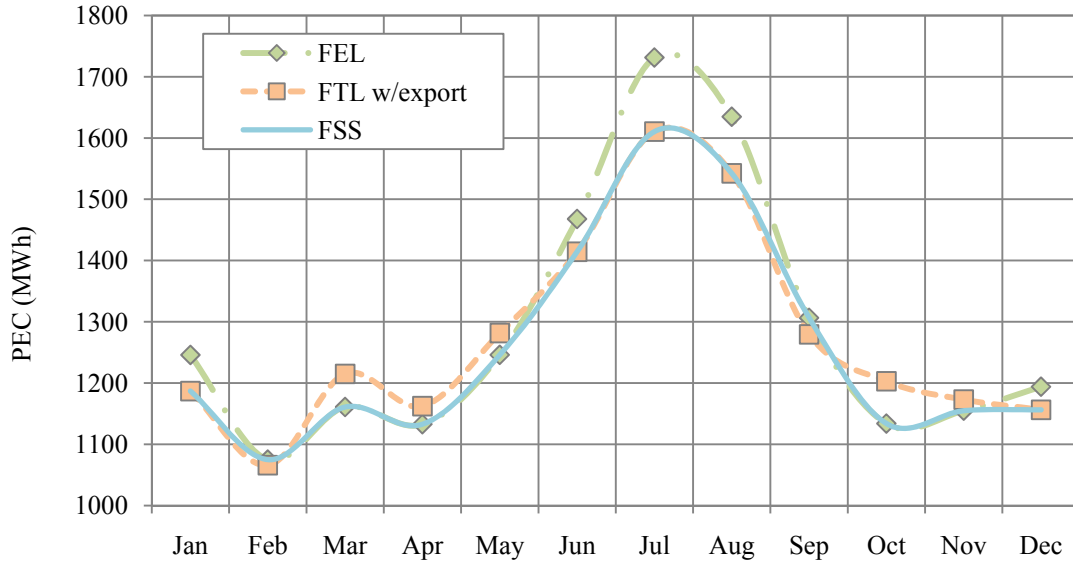
Figure 11.2   Comparison of the monthly PEC under FEL, FTL with export, and FSS operational strategies

11.1   CDE Distribution

Figure 11.3 expresses the distribution of CDE by source for the different CCHP system's operational strategies. For FEL, the majority of the emissions are from the on-site combustion in the PGU (70.7%). On the other hand, for the FTL with export and the FTL without export, most of the emissions are a result of the delivered electricity (51.0% and 56.1%, respectively) followed by natural gas combustion in the on-site PGU (39.3% and 35.3%, respectively). For the last operational strategy, FSS, on-site PGU combustion of natural gas accounts for 65.5% of the emissions and delivered electricity makes up 20.1% of the emissions. Therefore, for the FTL strategies, the delivered electricity is the primary source of CDE, while for FEL and FSS strategies, the PGU on-site combustion is the dominant contributor to emissions. For all the cases, the emissions from the on-site combustion of the boiler are low, between 4.8% and 10%. For the reference building,

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93.2% of the CDE are produced from the delivered electricity while only 6.8% comes from fuel consumption. These proportions change when CCHP systems are used. For FEL and FSS strategies 88.5% and 81.7%, respectively, comes from fuel utilization. On the other hand, for FTL with and without export, 51.9% and 45.8%, respectively, comes from fuel utilization.
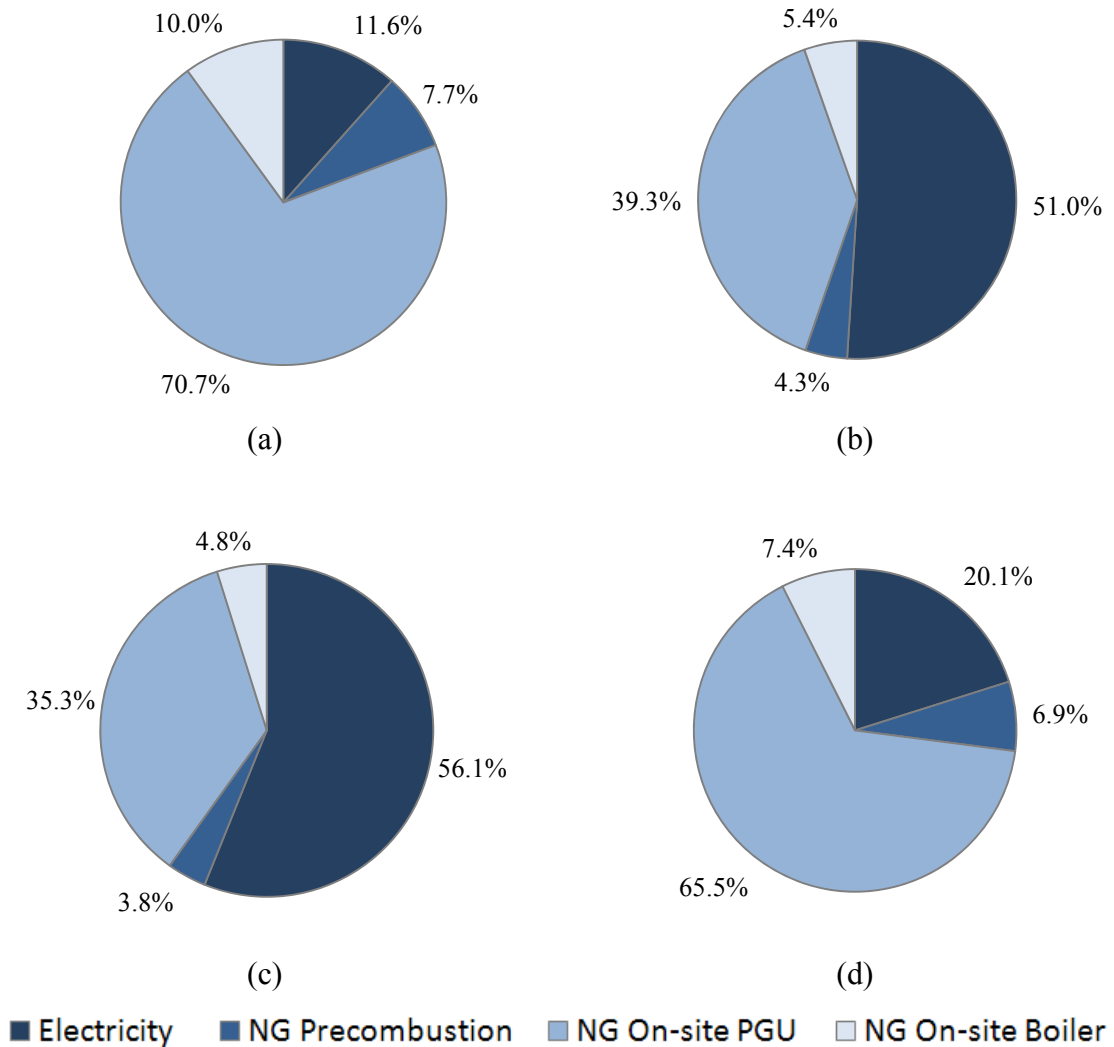
Figure 11.3   Distribution of CDE by source for CCHP system operating under (a) FEL, (b) FTL with export, (c) FTL without export, and (d) FSS

11.2 Evaluation of Carbon Offsetting through the Purchase of Carbon Credits

Figure 11.4 illustrates the effect of carbon credits by giving the total annual operational cost as a percent variation from the reference case for varying carbon credit values (in $/t of CO_2-equivalent). As the carbon credit value increases, the operational cost of the CCHP system decreases. Having the largest CDE reduction from the reference case among the operation strategies, the FEL and FSS strategies stand to benefit the most from carbon credits. For these strategies, the operational cost can be reduced from about 0.5% below the reference case for no carbon offsetting to about 6% below the reference case for carbon offsetting with a carbon credit value of $10/t of CO_2-equivalent. The operation strategy that would benefit the least from carbon credits is FTL without export, with cost reductions from 3.5% below the reference case to 6.4% below the reference for carbon credit values of $0/t of CO_2-equivalent and $10/t of CO_2-equivalent. Due to the different slopes in the cost lines, it is possible for the lowest cost operating strategy to change as the carbon credit value changes, though not the case in this study. While offsetting emissions by purchasing carbon credits is currently voluntary, the potential financial benefits from lowering emissions through the operation of a CCHP system are important to estimate.
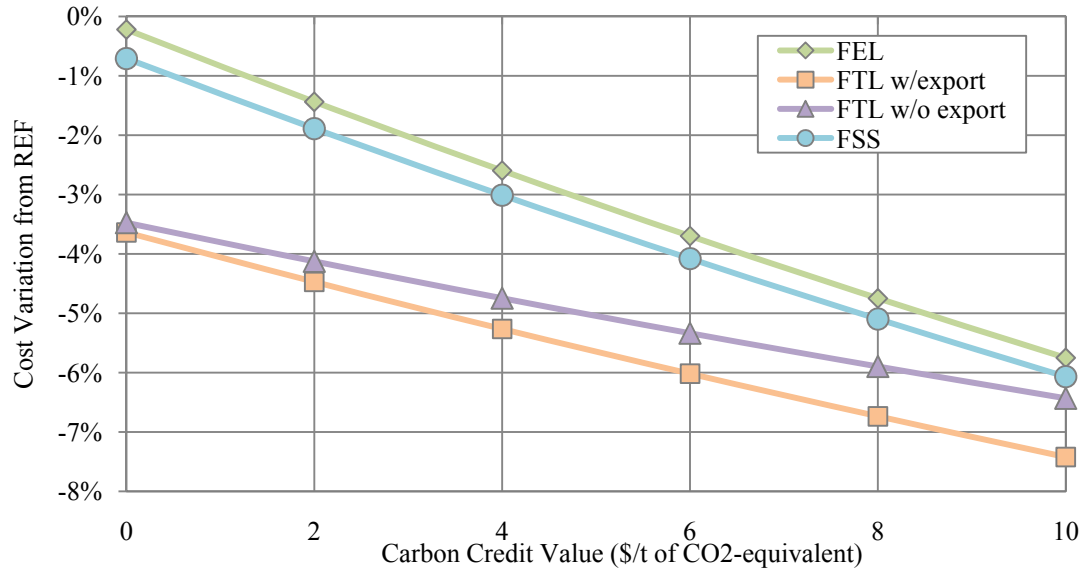
Figure 11.4   Effect of the carbon credit value on the total CCHP system operational cost

11.3   Estimation of Capital Costs

Figure 11.5 presents the capital cost that can be invested to upgrade to a CCHP system for different payback periods assuming a carbon credit value of $6/t of CO_2-equivalent. This figure illustrates that the FTL with export allows the largest amount of extra investment while the FEL provides the least amount of added investment. For a typical payback period of 3 years, an additional $87,286 can be invested to upgrade from the reference case to a CCHP system under FTL with export. For the same payback period, an additional $53,646 can be invested for a system operating under FEL. This represents an additional 63% of available capital for the CCHP installation if the system is operated to FTL with export as opposed to FEL.

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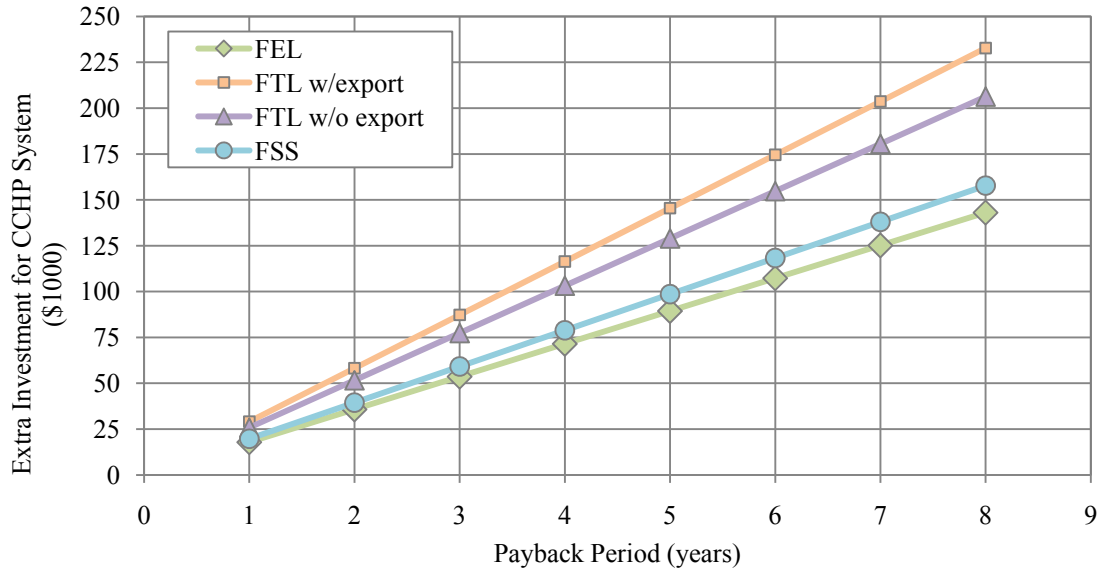
Figure 11.5   Capital investment available to upgrade to a CCHP system for different payback periods using a carbon credit value of $6/t of CO_2-equivalent

11.4   Effect of Electricity Export Price

Finally, Figure 11.6 illustrates the effect of the export electricity price on the annual cost of the CCHP system under FTL with export for different carbon credit values. The values on the x-axis represent the ratio of the export electricity price to the price for imported electricity, while the y-axis gives the operational cost as a percent variation form the reference case. As the ratio increases, so does the cost reduction. Also, this figure confirms that higher values of carbon credit yield higher reductions in the cost of operation. For the particular case of zero carbon credit value, the operational cost is 3.5% lower than the reference case if the ratio is equal to zero (basically no export) and decreases to 3.8% below the reference case if the ratio is equal to 1. However, for a carbon credit value of $6/t of CO_2-equivalent the operational cost is 5.8% lower than the reference case if the ratio is equal to zero and decreases to 6.1% below the

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reference case if the ratio is equal to 1. This can be more significant for other cases and locations if there is proportionately more electricity to export during the CCHP system operation.

Figure 11.6   Effect of the electricity export price on the total operational costs of the CCHP system for FTL with export

CHAPTER 12

CONCLUSIONS

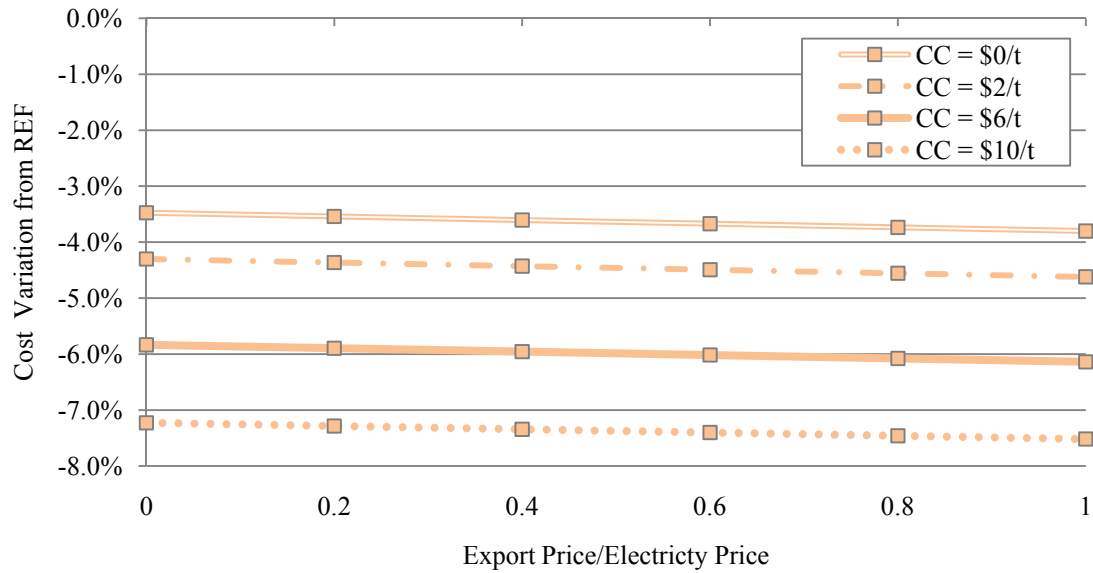The economical, energetic, and environmental benefits of CHP and CHP-ORC systems for a small office building in different North American climates were reviewed for FELc operation. The results demonstrated that, in general, operating the CHP and CHP-ORC systems during typical office hours is more beneficial than operating the systems 24 hours a day. For all the evaluated cities, the use of the CHP system increased the Energy Star rating from the rating of the reference case. In addition, the use of the optimized CHP system increased the rating above 75 for all the evaluated cities, which makes them eligible to receive the Energy Star label and allows the buildings to obtain LEED-EB points towards the 40 points needed to achieve LEED-EB certification. Results also indicated that the use of the CHP-ORC system reduced the cost, PEC, CDE, and fuel consumption for all the evaluated cities as compared with the CHP operation. Also, the results indicated that the CHP and CHP-ORC system performance strongly depends on the location where it is installed.

The role of the PGU in terms of operational strategy and engine size was more closely examined through simulations of CCHP and CHP systems for a small commercial office building under different costs structures. This was extended with a study that combined an ORC to the CHP and CCHP systems. The size of the engine was found to have an impact on the performance of the different systems, with some results varying by

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over 10% for different size engines. For a given operational strategy, better cost and PEC results occurred as the engine size decreased.

Under the continuous operational strategies, the systems were generally not favorable when compared to the reference case. While reduction in CDE for the FEL and full-load strategies were mostly possible, the associated costs were higher. For example, the CCHP system results in at least 23% higher costs than the reference case and over 75% higher costs in Chicago, where a block utiliy schedule is present. The addition of the ORC under these strategies lowers the cost, PEC, and CDE because any unused heat is converted to electricity thereby reducing the grid and fuel consumption. For the continuous strategies, the CCHP system outperformed the CHP system because of higher waste heat utilitzation. The same can be said for the CCHP-ORC system versus the CHP-ORC system. The simulations revealed that the best continuous operating strategy will depend on the engine size, location, and objective of the facility.

Optimizing the systems to minimize cost or PEC provided improvements over the system without optimization. This was in large part due to turning off the system when beneficial to do so, which, for most cases, occured most of the time (70-95%). The performance of the systems under cost and PEC optimization was found to be close to or better than reference building, with the exception of the operational costs in Chicago. However, when compared the reference building, the CDE optimization was only able to reduce CDE below the reference case emissions, but the cost and PEC was still above those associated with the reference case. The optimized CHP system generally provided lower costs and lower PEC over the optimized CCHP system and the addition of an ORC

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under the optimized strategies improves the performance of the optimization criterion but a tradeoff may exist with the cost. The choice between an optimized CCHP-ORC system and an optimized CHP-ORC system was found to depend on the priorities of the operator and engine size.

Operating the CCHP or CHP systems according to the FTLc strategy, where the system turns off if the load is below the engine's minimum load, provided results comparable to the cost- and PEC-optimized cases. This can be important because the FTLc strategy is simpler than any optimization strategy.

Using the reference case's average electricity price for cost calculations of the CCHP building tends to underestimate the cost when compared to using the real electricity rate structure, however, not significantly. Also, using an average natural gas price can under- or overestimate the costs predicted using monthly rates. Together, using average prices for cost computing under the continuous operational strategies results in cost deviations on average of -5%, 2%, and -12% from using the actual pricing data in Boulder, Duluth, and Chicago, respectively. If national average price values were used for electricity and/or natural gas the predicted operational costs could deviate even more from the cost predicted as a result of using actual prices.

For a large office building located in Chicago, IL, the cost, primary energy consumption, and carbon dioxide emission of a CCHP system using a load-share turbine while operating under FEL, FTL, and FSS strategies was examined. In addition, the source of carbon dioxide emissions, operational costs under carbon offsetting, and available capital costs were determined. Under all the strategies, operation of the CCHP

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system reduced the operational cost (for a zero carbon credit value), primary energy consumption, and carbon dioxide emissions by an average of 2%, 12%, and 40%, respectively, from the reference case. The use of the CCHP system shifts the source of carbon dioxide emissions away from delivered electricity and towards fuel consumption. Offsetting carbon dioxide emissions by purchasing carbon credits can successfully yield financial reward for reducing emissions. Having the largest CDE reduction from the reference case among the operational strategies, the FEL strategy stands to benefit the most from carbon offsetting. For this strategy, the operational cost can be reduced from 0.2% below the reference building without carbon offsetting to 6% below the reference building for a carbon credit value of $10/t of CO_2-equivalent. Finally, for typical payback period of 3 years and a carbon credit value of $6/t of CO_2-equivalent, an additional $87,286 can be invested to upgrade to the CCHP system operating according to FTL with export.

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