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Evaluation Of Propane Fueled Chp Systems For Small Commercial Applications

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EVALUATION OF PROPANE FUELED CHP SYSTEMS

FOR SMALL COMMERCIAL APPLICATIONS

By:

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This thesis evaluates the effects of Combined Heating and Power (CHP) systems with a Propane fueled spark ignited engine as prime mover used in a small commercial building. The system was evaluated in five different U.S. cities. The most common operating modes, thermal load following (FTL) and electric load following (FEL) were evaluated, and an optimized operating mode was developed and investigated. The optimized operating mode is a hybrid (FHL) of FEL and FTL operation. Methodology for the derivation and application of these models is presented. Also, the economic effects of Diesel and Natural Gas were investigated. The results for all five cities and all three operating modes were gathered and compared with a conventional system. Comparisons were made based on cost, primary energy consumption, and carbon dioxide emissions. It was concluded that the feasibility of CHP had great potential, but is highly dependent upon the location of the system.

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NOMENCLATURE

CHP	Combined Heating and Power
η_{pm}	Prime Mover Efficiency
W_{mech}	Mechanical Work Output
$\dot{m}_{fuel}$	Mass Flow Rate of Fuel
LHV	Fuel Lower Heating Value
F_{pm}	Fuel Energy Input Into Prime Mover
η_{gen}	Electric Generator Efficiency
E_{gen}	Electric Power Generated
$Q_{rejected}$	Heat Rejected by Prime Mover
Q_{rec}	Heat Recovered by System
RF	Exhaust Heat Recovery Factor
ξ_{HX}	Heat Exchanger Effectiveness
E_{req}	Electric Power Required
F_{boiler}	Fuel Energy Input into Boiler
Q_{boiler}	Heat Generated in Boiler

η_{boiler}	Boiler Efficiency
$\cos t$	Energy Cost by Content
$COST$	Total Operational Cost
PEC	Total Primary Energy Consumption
pec	Primary Energy of Fuel by Content
CDE	Carbon Dioxide Emissions
ef	Carbon Dioxide Emission Factor
K	Constant of CHP Operation

CHAPTER 1

INTRODUCTION

Combined heating and power (CHP) systems use a prime mover of some sort (typically either a spark or compression ignition combustion engine or a turbine engine) delivering useful mechanical power to an electrical generator which in turn creates useable electrical power in order to satisfy a given electrical demand including lights, equipments, and the electricity required for cooling. Then the waste heat from electric power generation is used to provide the heating needs of the facility.

This study investigates the performance of propane fueled CHP based on primary energy consumption, operational cost, and reduction of emissions. This chapter presents an extensive literature review as well as previous research and existing technologies on propane fueled cogeneration systems. To evaluate the performance of CHP systems, the first step is to estimate the energy consumption. Chapter 2 presents the model to estimate the CHP energy consumption as well as the primary energy consumption, operating cost, and carbon dioxide emissions. This chapter also presents the models to simulate the CHP system running under different modes of operation. Chapter 3 presents the results and discussions of the CHP system operating under different weather conditions and the comparison of this system with the conventional system.

1.1 Literature Review

This section includes a description of distributed generation technology and its importance; an introduction to CHP technology and its benefits; an overview of Propane as a fuel; and load following options for the CHP system.

1.1.1 Distributed Generation

On-site power generation has been a common fixture in industrial applications for many years, however residential and light commercial uses for distributed generation (DG) have garnered considerable attention in recent years. The energy crisis in California, the threats of terrorist attacks on U.S. infrastructures, and the blackouts of the Northeastern U.S., Canada, and Europe in the summer of 2003, have all given rise to public interest in distributed generation, especially in the residential sector [1]. A system of distributed power generation with little, or no, grid dependency would be functional even under threats of attacks. Many deregulation and restructuring efforts have been attempted, but these efforts have been met with resistance [2]. Many state governments have initiatives underway to further increase the use and development of DG systems, but none have fully incorporated DG systems into any energy plan [3].

The major issue facing DG systems is cost. Renewable energy DG systems like photovoltaic panels, wind turbines, and small hydroelectric are much more expensive than systems that utilize a continuous fuel source such as reciprocating engines, microturbines, and fuel cells; also the continuous fuel systems can be dispatched most anywhere, while most of the renewable sources are dependent on regional climate or topography [4]. CHP systems, however, have proven to be effective in many climates, even in the tropics where there is little need for space heating [5].

1.1.2 Combined Heating and Power

A combined heating and power system is a system that simultaneously produces electricity and a useful heating effect. The CHP system consists of a prime mover that generates electricity and a waste-heat recovery device. Prime movers in CHP systems can be steam turbines, combustion turbines, reciprocating engines, Stirling engines, and fuel cells. Each of these prime movers has distinct advantages and disadvantages for CHP usage. As the prime mover generates electricity, the heat that is expelled from the device through exhaust and jacket water is captured through a heat exchanger and delivered to the building's air handling system, domestic water heater, or to some industrial process requiring heated water or steam. CHP systems have been in use for over one hundred years, but have been predominately utilized in large scale industrial applications [6]. However, residential CHP systems are not uncommon in many other countries throughout the world [6,7], and attempts have been made to market a residential model in the United States as early as 1986 [8]. Since approximately 20% of the energy produced in the United States is used by the residential and commercial sector, increasing energy efficiency in this sector would cause a significant change in overall energy consumption [2]. Although some definitions may vary, one report defines any generation system with less than 20kW capacity as micro-generation [6]. Micro-CHP systems are being extensively researched and can potentially provide much greater energy efficiency in residential applications.

According to the U.S. Department of Energy, 49% of all electricity is used for space heating and cooling, and another 13% is used for water heating [9]. If these needs can be fulfilled by the capture of waste heat from power generation, there would be quite a considerable fuel saving. With traditional coal fired power plants giving an efficiency of around 33% [2], CHP would represent monumental energy savings with efficiencies over 80% [10]. When compared to modern technologies for the separate production of electricity and heat, micro-CHP systems give a primary energy savings of up to 25% and a reduction of up to 40% in polluting emissions [11]. Models and thermodynamic equations have been used to predict the efficiency and environmental impact of CHP systems, including the estimated carbon dioxide emissions [12]. Higher efficiency of electrical generation devices will lead to a decrease in the use of fossil fuels, which would inevitably lower harmful emissions and decrease the rate of depletion of these fuels.

CHP systems have been found to be an economically sound power generation system. An industrial CHP system in Istanbul, Turkey was calculated to have a payback period of only 3.23 years [13]. Mathematical models have been developed in order to properly size the equipment and to determine optimum operational strategies [14,15]. Sufficient information is available to construct an economically alluring CHP system.

According to a feasibility study conducted by the American Society of Mechanical Engineers, propane can be used as the fuel source for cogeneration systems that employ either reciprocating engines or gas turbines as prime movers [5]. Reciprocating engine products are available for a range of cogeneration applications and are available in sizes ranging from a few kilowatts to over 5 MW. Reciprocating engines have a number of characteristics that make them good selections for CHP. These characteristics include the ability to start quickly, shut down quickly, availability in small sizes, high part-load efficiencies, high reliability, and the ability to follow loads [16].

In order to be readily accepted into the residential market, a CHP system must have a low initial cost, a short payback period, and a relatively long maintenance interval. The biggest obstacle facing micro CHP systems is initial cost [11]. There are systems being implemented worldwide based on Stirling engines and fuel cells [7, 17, 18], but presently the CHP system with an internal combustion engine as the prime mover has the lowest first cost. There are some packaged CHP units already on the market. The advantages of these packaged systems over other CHP technologies are low capital cost, reliable onsite energy, low operating cost, ease of maintenance, and wide service infrastructure. These units range in electrical capacity from 1 to 100kW, with a model suitable for most applications. The maintenance period for these systems, which is prolonged by running the engine at lower speeds, can be as long as 30,000 hours [10]. Internal combustion engines also operate very well under partly loaded conditions, a power range where micro-turbines are less than desirable [19, 20]. With units readily available and with long maintenance intervals, CHP systems that utilize an internal combustion engine will be the quickest to become adopted on a grand scale.

1.1.3 Propane as a Fuel

Propane is an attractive fuel for CHP systems. In internal combustion engines, propane burns with little air pollution and little solid residue, it does not dilute lubricants, and it has a high octane rating [21]. Propane is ideal for rural areas that are beyond the reach of natural gas piping systems; it can be purchased in small quantities from gas stations or it can be delivered to one's home in larger quantities.

As one of the cleanest burning fossil fuels, propane is environmentally friendly. When used to fuel a spark-ignited engine, the emissions of unburned hydrocarbons and carbon monoxide were one tenth the emissions of a gasoline engine running at the same speed and the same ignition timing [22]. Much of the sulfur dioxide, the chemical known to produce acid rain, found in the atmosphere is attributed to coal-fired power generation. Neither the burning of propane nor the production of propane releases significant acid contaminants. Because propane is gaseous at atmospheric conditions, it does not pose a threat to soil and groundwater, and propane storage tanks can be placed above or below the ground without worry. Proper use of propane significantly decreases the threat to the welfare of the environment posed by other fossil fuels.

Propane also performs very well in an internal combustion engine. Since propane burns cleaner with less carbon build up and oil contamination, engine wear is reduced and the life of many engine components, like rings and bearings, is extended. Propane has an average octane rating of 104, which is significantly higher than gasoline's range of 84-97; higher octane fuels can run at much higher compression ratios, which means a more efficient engine [21]. Propane fueled reciprocating engines used for cogeneration applications have given the following characteristics; electric efficiencies of 25-50%, sizes ranging from 0.05-5 MW, and usable temperatures for CHP of 180-500ºF [23]. When run in the same engine, the brake specific fuel consumption, a measure of the fuel flow rate divided by the brake power, is less with propane than with gasoline [22]. These performance parameters make propane a very attractive fuel for internal combustion engines.

1.1.4 Load Following and Energy Storage

For CHP applications, there are few options as to the load the unit will carry: the CHP can be used to supplement the current power system, as in peak shaving, and only carry part of the electric load required; the CHP can meet the electric load of the building, often not producing enough waste heat to meet the thermal load; or the CHP can follow the thermal load, often producing excess electricity. Peak shaving is often used in industrial settings when there is a chance that the building or process may require more power than the grid can produce. The following of the electrical load allows a building to be completely independent from the grid, but requires a supplemental heating system because the thermal load is usually not met. Often a CHP system will need to produce more than the necessary amount of electricity to meet the thermal load. In this case, the excess electricity must either be sold back to the utility grid or stored onsite. Electricity storage onsite is often accomplished with batteries. Research has shown that the thermal load following system gives higher system efficiency than that of the electrical load following system for residential and small commercial applications [24]

1.2 Previous Research of Propane Fueled CHP Systems

Much research has been done on propane fueled CHP systems, and much information can be gained from these projects. This section includes a description of a few of these projects, and the similarities and differences between the previous projects and this research.

1.2.1 Propane Tests at Chesapeake Building

The University of Maryland performed a project to demonstrate the feasibility of using propane in large CHP applications (>50 kW). They modified two existing CHP systems originally operated on natural gas to be able to operate them using propane. These two CHP systems were used in an administrative office building that has four floors totaling 52,700 ft2 of floor space and two air conditioning zones each consisting of two floors. The first CHP system consists of two natural gas engine driven air conditioning units to provide cooling, which is delivered to a roof top unit "1." Heat is recovered both from the engine jacket water circulating throughout the engines in a liquid-to-liquid heat exchanger and also from the exhaust gases from both engines using air-to-water heat exchangers located between the engines. The heated fluid is delivered to the regeneration side of the liquid desiccant system to raise the temperature of the liquid working fluid – an aqueous lithium chloride solution. The second CHP system consists of a microturbine (Capstone Model C60 high-pressure natural gas unit) that provides 60kW to the building, a 20-ton single-effect lithium bromide water absorption chiller designed to use the exhaust gas of the microturbine directly as its heat input source, a solid desiccant system, and a roof top unit "2." The absorption chiller is used to provide chilled water that is delivered directly to the existing roof top unit "2." The exhaust of the absorption chiller is used to regenerate the solid desiccant system. It was found that the conversion from natural gas to propane had no impact on the energy consumption and performance of the engine driven air conditioning units, but slightly reduced the efficiency of the microturbine at higher loads [25].

It can be clearly observed that the demonstration project described above differs from this thesis since it targets large building applications as opposed to targeting small commercial or residential CHP applications. Also, the system configuration will be different. This thesis is a combined heat and power, in which a propane engine will be used to provide electricity to the building and to the vapor compression system, and the waste heat will be used to provide space heating and domestic hot water.

1.2.2 Yanmar Micro-CHP

Micro-CHP systems are currently being used in many small commercial applications in Japan. In order to accelerate the commercialization of these systems in the United States, the Propane Education and Research Council (PERC) has initiated the performance testing and evaluation of Yanmar CHP systems to be led by the Gas Technology Institute (GTI). The project will use an internal combustion engine as the prime mover, and the heat released from the exhaust and jacket water is captured as steam or hot water for space heating and cooling, water heating, and/or other thermally activated technologies. Performance data will be collected in order to validate the performance of a propane-fueled Yanmar CP-Series cogeneration system. The project is currently waiting for the micro-CHP unit to arrive at the GTI test facility [26]. This project is very similar this thesis since it investigates the performance and feasibility of a micro-CHP for residential use, however this thesis will not consider thermally activated technologies for cooling.

1.2.3 Propane-Fueled CHP: Green Mountain Coffee Roasters

PERC funded a research effort that would provide continuous power to Green Mountain Coffee Roasters (GMCR) coffee roasting and packaging operations. The project would also compare economics of on-site power production with economics of grid-delivered electricity; monitor energy production of on-site CHP system; analyze existing state laws and utility regulations to increase distributed generation projects in rural Vermont; and generate a CHP model to promote additional distributed generation activities. In 1999, a 95kW CHP unit was installed in conjunction with GMCR's original roaster line. The success of this system led to the installation of a 280kW CHP plant for an expanded roaster line, bumping the 95kW system to standby status. Heated water from the water jacket is sent to super-insulated tanks that preheat wash water for processing and other building uses. An air/water heat exchanger on the engine exhaust preheats water in the building's hydronic space heating system [27].

This system differs from the proposed system for this thesis mainly because of its size. This is an industrial application, where this thesis is looking for a residential application for CHP.

1.2.4 Potential of Propane as a Microturbine Fuel

Even though this thesis uses an internal combustion engine as prime mover, it is important to emphasize that research has been performed on microturbine using propane fuel. The idea is to use microturbines in rural areas that are beyond the natural gas pipeline distribution system. Propane does, however, present a few issues not encountered with natural gas. Many microturbines require a higher pressure than propane vapor in a storage tank can provide. In this case pumping and vaporizing equipment is required. Pumping and vaporizing is also required to ensure that no liquid propane enters the combustor. A Capstone Model C30 microturbine was operated in Columbia Station, OH. The microturbine was operated in much the same way as natural gas, and was found to have similar exhaust emissions. The microturbine operated reliably for a total of 1,756 hours in a fourteen month period showing that propane is a viable fuel option [28].

1.3 Evaluation of Existing Technologies of Propane Fueled CHP Systems

Residential CHP systems have been marketed around the world with the most success in Europe and Asia. Aisin, a Japanese automotive manufacturing corporation, now offers a 6kW cogeneration system that uses a 3-cylinder spark ignited engine as its prime mover and boasts overall efficiencies of 85% [29]. WhisperGen offers a 1kW unit with a Stirling engine prime mover that's efficiency is greater than 90%; these units are mainly distributed in New Zealand and the United Kingdom[30]. SenerTec DACHS has a 5.5kW CHP unit built around a single cylinder internal combustion engine and is distributed across Europe [31]. Honda has developed a 1.2kW compact cogeneration unit that has a maximum efficiency of 85.5%. These units are being marketed worldwide, and Climate Energy is distributing them in the United States [32]. Many companies offer CHP units, and with increasing competition these units will become more readily available for general household use.

Polar Power, Inc. also offers a commercially available unit that is advertised as being capable of using propane in a combined cooling, heating and power application. This unit utilizes the shaft power of a gas engine to drive both a DC generator and a heat pump compressor. The exhaust gas heat is reclaimed to provide water heating. The unit claims 34,000 Btu/hr for space cooling in the form of chilled water, 36,000 Btu/hr for space heating in the form of hot water, 30,000 Btu/hr for domestic water heating and 6 kW of DC electrical generation. In the heating mode, the space heating portion can be combined with the domestic water heating for a total of 66,000 Btu/hr in water heating capacity [33].

Marathon Engine Systems has already developed many applications completely dedicated to CHP. The units developed range from 1 to 5 kW and can be powered by either propane or natural gas. Marathon has developed a number of different cogeneration systems, but each system is powered by the same 272-cc, single-cylinder, four-cycle, liquid-cooled 5kW engine rated at 7.5 HP at 1200 to 3600 rpm. The engine also features a 4000-hour service interval and a 40,000 hour life. The Marathon engine uses a top-mounted exhaust gas recuperator with a three-way custom catalyst design to recover heat from the engine, generator, and exhaust. According to Marathon, this type of system provides cogeneration of heat and power with approximately 90% efficiency. Marathon is the principle supplier of this type of system in the U.S. However, its European partner, Power Plus Technologies provides a similar type of system to European communities. Power Plus supplies the European market with the Ecopower gen-set, a similarly developed 2 to 4.7 kW system. The European counterpart of the Marathon system also has current applications in car washes, laundromats, schools, lodges, hotels, small industry, agriculture, sport centers, and swimming pools, pointing out how versatile these systems have become [34].

Another prime mover option for a propane fueled cogeneration system is a Stirling engine. DTE Energy Technologies has recently introduced its ENX 55 energy system, a 55 kW cogeneration package powered by a Stirling engine that can operate on such fuels as propane, natural gas, flare gas, methane, wood gas, or biogas [35]. Stirling engines are ideal prime movers for cogeneration systems due to the fact that they are classified as external combustion engines, which are highly efficient and can operate on essentially any heat source. Heat is supplied to a Stirling engine from any external source, such as a burning gas, which causes the working fluid to expand, moving one of the two pistons inside a cylinder. Due to the fact that the Stirling engine has no valves, tappets, fuel injectors, or spark plugs and it also has fewer moving parts than a conventional internal combustion engine, it is much quieter and more efficient. Typically, Stirling engines are used to power micro-cogeneration boilers which have a need for small engines with a capacity between 0.2 and 4 kW, for which the Stirling engine is a good alternative [36].

According to Diesel Progress, a Stirling engine previously supplied by STM Power, Ann Arbor, Mich., provided enough rotational power to produce 55 kW of electricity and a heat output of 310,000 Btu/hr. In this type of system, piston linear motion is converted to rotary motion in order to drive a generator. Waste heat rejected in the engine exhaust is passed through and air-to-water heat exchanger and water that is heated to approximately 140^{o}F can then be used for space heating or some other application. DTE Energy Technologies reports that the ENX 55 unit provides an electrical efficiency of 31%, with an efficiency of 82% in the total CHP system. However, one drawback of using a Stirling engine to drive the system is that the engine requires extremely high temperatures, between 1472^{o}F and 1832^{o}F [35].

Intellicon, a company located in southern California, has been actively involved in both the development of cogeneration computer control programs and in the design, supply, and operation and maintenance of these cogeneration systems. In the past, the company worked with McDonald's in order to develop small gas-powered cogeneration systems for stores in the San Diego area. Intellicon has successfully installed a propane-fueled cogeneration system in the McDonald's located in Ramona, California. In spite of the fact that propane is more costly than natural gas in the San Diego area, the economics of using propane were still favorable, partly because Petrolane, a national propane supplier, has sponsored the project. The cogeneration system installed in the Ramona McDonald's franchise is comprised of four interconnected modules which include the switchgear and control system, the engine/generator package, an absorption chiller, and a fourth module which consists of pumping units, a heat exchanger, and controls. The engine/generator package was supplied by Hawthorne Engine Systems and employs a Caterpillar 3304 engine and Cat synchronous generator which uses propane as fuel and generates 65 kW.

Jacket water heat recovery was the only heat recovery method being used upon installation of the cogeneration system. However, exhaust heat recovery can easily be applied to this system by means of an air-to-water heat exchanger if additional process heat or space heating is needed. The system utilizes waste heat to run an absorption chiller, but could easily eliminate this piece of equipment and direct all heat recovery to space heating methods if no cooling or refrigeration is required. Intellicon currently plans to cooperate with Petrolane in the implementation and operation of cogeneration systems in other local McDonald's franchises [37].

After hundreds of residential cogeneration systems have been successfully installed in Japan and Europe, several cogeneration manufacturers are now offering models in the U.S.. The types of engines used in these systems can either be internal combustion generators or Stirling engines, which can run on a variety of fuels such as propane, natural gas, or even concentrated solar energy or biomass. A typical 6 kW cogeneration unit provides 10 gpm of hot water at 140ºF to 150ºF, which can be used to heat an entire home. These residential micro- CHP systems generate an overall efficiency of approximately 90%, which is very attractive when compared to 30-40% electrical efficiencies from conventional methods such as central power stations. Current micro-CHP systems range anywhere from 1 kW to 6 kW and are about the size of any major home appliance. One specific new technology offers a residential micro-cogeneration system that uses a small capacity engine to simultaneously produce 1.2 kW of electric power and 11,000 Btus of heat in the form of hot water.

The cost for the 1.2 kW cogeneration system is anticipated to be twice as much as conventional methods. However, the unit cost for the 2 to 6 kW system is on the order of $10,000 to $20,000 with additional installation costs. Manufacturers estimate that installation costs for systems ranging from 2 to 4.7 kW in new homes to be approximately $4,000. Even though the 1.2 kW cogeneration system will only provide half of the annual household electrical needs, it can still be operated to its full capacity for less than purchasing the equivalent amount of fuel and electricity so long as the cost of electricity remains below $0.085/kWh [38].

Climate Energy in Medfield, MA, is currently conduction a joint venture along with ECR International and Yankee Scientific to test a 1.2 kW micro-CHP system for residential use. The cogeneration packages were installed in 25 local residences. The cogeneration system installed was developed by Honda Motor, Tokyo, who has already sold over 50,000 1-kW units for single-family homes in Japan. SenerTec, a similar firm in Schweinfurt, Germany, also markets a comparable 5-kW system for apartment buildings in Europe. These types of systems have excellent payback if you live in a region that gets very cold in the winter and a lot of money is spent on electricity for heating purposes. In these cases, a typical micro-CHP system has the capability to pay for itself in as little as two years and save as much as $500 annually thereafter. However, if a great deal of heating is not required annually, the system could take as long as 10 years to pay for itself. For this reason, micro-CHP systems are an economically attractive alternative for homes that require more than 4,000 heating hours per year. According to Peter Banwell of the U.S. Environmental Protection Agency, approximately 30 million American homes fall into that bracket and many of these residences are in regions of the country such as Massachusetts and Connecticut where electrical rates have climbed as high as $0.20/kWh [39].

1.4 Objectives

- Develop a model to simulate the performance of a propane fueled CHP system following the thermal and electric load.
- Develop a new CHP operation mode in which the CHP system follows a hybrid electric-thermal load (FHL). The new proposed operation mode is evaluated and compared with the CHP system operating following the thermal load and following the electric load. This evaluation and comparison is based

on Primary Energy Consumption (PEC), operating cost, and carbon dioxide reduction.

- Develop a model to estimate the performance of the building without a CHP system incorporated (reference building). This will allow comparing the performance of the building with and without the CHP system in terms of on PEC, operating cost, and carbon dioxide reduction.
- Evaluate the performance of propane fueled CHP systems for different weather conditions through US. In addition the evaluation of different fuel will be briefly discussed in this investigation.

CHAPTER 2

SYSTEM MODELS AND OPERATING MODES

The operation of CHP systems, while obviously dependent upon the seasonal atmospheric conditions, which determine thermal and power demand loadings, is ultimately controlled by one of several possible operation modes. Two of the simplest operation modes are to run the prime mover in accordance to either electrical or thermal demand. Cardona and Piacentino [40] refer to these two styles as Electric Demand Management (EDM) and Thermal Demand Management (TDM). The choice between EDM and TDM is usually governed by the loading of the prime mover as well as a few extraneous circumstances including the ability to sell back electricity to the grid or store it on site for later use via some battery system. Also, the price of fuel versus that of electricity purchased from a traditional source can affect the management of a plant [14]. According to Cardona and Piacentino [40], the TDM management strategy is most commonly used where excess electricity produced can be sold back to the grid. Conversely, EDM is used in the desire to not waste any thermal energy rejected from the prime mover, but this is usually not as much of a concern if excess electricity can indeed be sold to the grid [40]. Jalalzadeh-Azar [41] performed a non-dimensional analysis of energy cost and primary energy consumption of CHP systems utilizing a gas fired micro-turbine. In this analysis the two main operational modes (following the electric load and following the thermal load) were evaluated. The results yielded an 11%

reduction in total energy consumption when the system operates following the thermal load versus the system following the electric load. This reduction was deemed to be in large part due to the higher level of waste heat utilization when the system followed the thermal load. It is important to note here, that under his analysis the varying regulations that exist throughout potential CHP implementation sites were beneficial when the system followed the thermal load as surplus electricity could be sold back to the grid. Although Cardona [40] and Jalalzadeh-Azar [41] have performed analysis on CHP systems operation following the thermal and electric loads, this thesis investigates the effect of these two modes of operation on the PEC, operation cost, and carbon dioxide emissions, for CHP and HP systems. In addition a new proposed operation mode is introduce in this chapter.

The reduction of carbon dioxide is an important factor that is considered in this investigation. If the operation cost of CHP systems is higher than the conventional systems, as long as energy savings are guaranteed, other benefits such as emissions reduction, among others, could overcome the economic weakness. Several researchers have evaluated and analyzed the benefits of CHP systems in terms of reduction of pollutants for different applications. Some of them include: Mago et al. [42], Pierluigi et al. [43], Möllersten et al. [44], Wahlund et al. [45], and Möllersten et al. [46], among others. In general, they reported that CHP systems have the potential and the ability to reduce the emission of carbon dioxide. Mago et al. [42] showed that CHP systems could significantly reduce emission of pollutants, making this technology a great tool to protect the environment while helping business to comply with environmental regulations.

This chapter presents the equations used to model the CHP evaluated in this investigation. Three different operation modes are modeled and investigated: CHP systems operating following the electric load, CHP systems operating following the thermal load, and an optimized hybrid electric/thermal load operation. A schematic of the CHP system is shown in Figure 2.1. For CHP systems the fuel is supplied to the prime mover to produce the electricity needed for the building including the electricity required to operate a vapor compression system for cooling. Then, the waste heat from the prime mover is used to provide heating when needed.

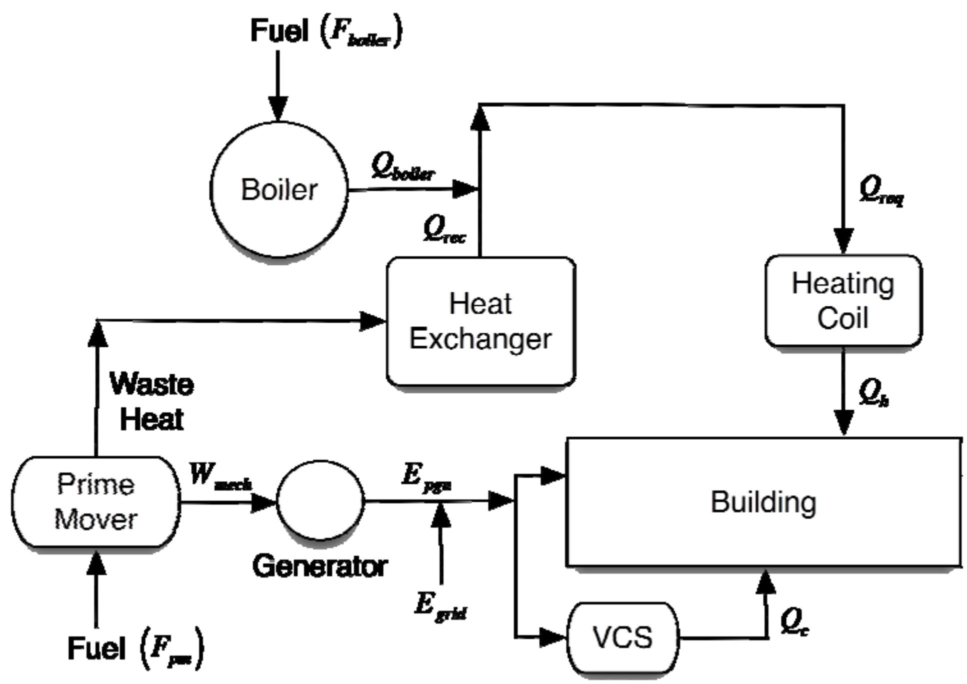


Figure 2.1 Schematic of the CHP System

2.1 Basic Definitions

The mathematical model for the combined heating and power system is dependent upon the amount of energy input into the prime mover, and how much of this energy is converted into mechanical work. The ratio of mechanical work output to energy input is defined as the prime mover efficiency:

$$\eta_{pm} = \frac{W_{mech}}{\dot{m}_{fuel} LHV} = \frac{W_{mech}}{F_{pm}} \tag{2.1}$$

where W_{mech} is the mechanical work produced by the prime mover, $\dot{m}_{fuel}$ is the fuel mass flow rate of the fuel, and LHV is the fuel's lower heating value. F_{pm} is defined as the total fuel energy input into the prime mover. The prime mover efficiency can usually be found through experimental methods. For an internal combustion engine, realistic values of efficiency are around 25%.

Since the mechanical work generated in the prime mover is used to generate electricity, the electric generator is also of great importance. The amount of electrical power produced for a given amount of shaft work input is defined as the generator efficiency, or η_{gen}:

$$\eta_{gen} = \frac{E_{gen}}{W_{mech}} \tag{2.2}$$

where E_{gen} is the electric power generated. The generator efficiency is usually given by the generator's manufacturer, and many generators run at an efficiency of 95%.

The amount of heat rejected by the prime mover is also indicated by the prime mover efficiency:

$$Q_{rejected} = F_{pm}(1-\eta_{pm}) \tag{2.3}$$

Due to irreversibility of the combustion process only a portion is available for recovery. Furthermore, due to losses in the heat exchanger, only a portion of the available heat will actually be recovered. These losses can be defined mathematically using correction factors, since the amounts will always be less than one. The factor of recoverable heat from the prime mover is defined as RF. Assuming a heat exchanger effectiveness, ξ_{HX}, the total heat recovered by the system as:

$$Q_{rec} = (RF)(\xi_{HX})F_{fuel}(1-\eta_{pm}) \tag{2.4}$$

2.2 CHP System Model Following the Electric Load (CHP-FEL)

When following the electric load for a given application, the CHP system is set to supply all of the electricity needed by the building plus the electricity needed to operate a vapor compression system. So if the electric power required is known, then the electric power that has to be generated by the prime mover-generator unit (PGU) is defined as:

$$E_{gen} = E_{req} \tag{2.5}$$

Where E_{req} is the building electric energy consumption (electric equipment, lights, vapor compression system etc).

The prime mover fuel energy consumption can be shown with respect to power generated and the component efficiencies:

$$F_{pm} = \frac{E_{gen}}{\eta_{pm}\eta_{gen}} \tag{2.6}$$

where η_{pm} is the prime mover thermal efficiency and η_{gen} is the generator efficiency. The efficiency of the prime mover is assumed to be constant and independent of the electric demand.

The recovered waste heat from the prime mover can be estimated from Equation (2.4). In this case, the recovered heat is used to handle only the heating load. Therefore, if the recovered thermal energy is not enough to handle the heating load, additional heat has to be provided by the auxiliary boiler of the CHP system. Therefore,

$$\text{If } Q_{rec} > Q_{req} \rightarrow Q_{boiler} = 0 \text{ or if } Q_{rec} \quad Q_{req} \rightarrow Q_{boiler} = Q_{req} - Q_{rec} \tag{2.7}$$

The amount of fuel energy required by the boiler is then defined as:

$$F_{boiler} = \frac{Q_{boiler}}{\eta_{boiler}} \tag{2.8}$$

where η_{boiler} is the boiler thermal efficiency.

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

$$F_m = F_{pm} \quad F_{boiler} \tag{2.9}$$

The cost of operation of the electrical load following system can then be calculated using fuel costs:

$$COST_{CHP.FEL} = (F_{pm} \quad F_{boiler})\text{cost}_{fuel} \tag{2.10}$$

where $\cos t_{fuel}$ is the cost of the fuel for the system.

Thermal energy efficiency from the use of CHP systems has to be assessed through primary energy consumption. PEC is defined as the amount of site energy consumption, plus losses that occur in the generation, transmission, and distribution of energy [47]. Therefore, the building PEC is determined

$$PEC_{CHP.FEL} = (F_{pm} \quad F_{boiler})pec_{fuel} \tag{2.11}$$

where pec_{fuel} is the site-to-primary energy conversion factors for the fuel.

The amount of carbon dioxide emissions given off by the system is defined as:

$$CDE_{CHP.FEL} = (F_{pm} \quad F_{boiler})ef_{fuel} \tag{2.12}$$

where ef_{fuel} is the emission conversion factor of the fuel. A flow chart of the model for CHP operation following the electric load is presented in Figure 2.2.

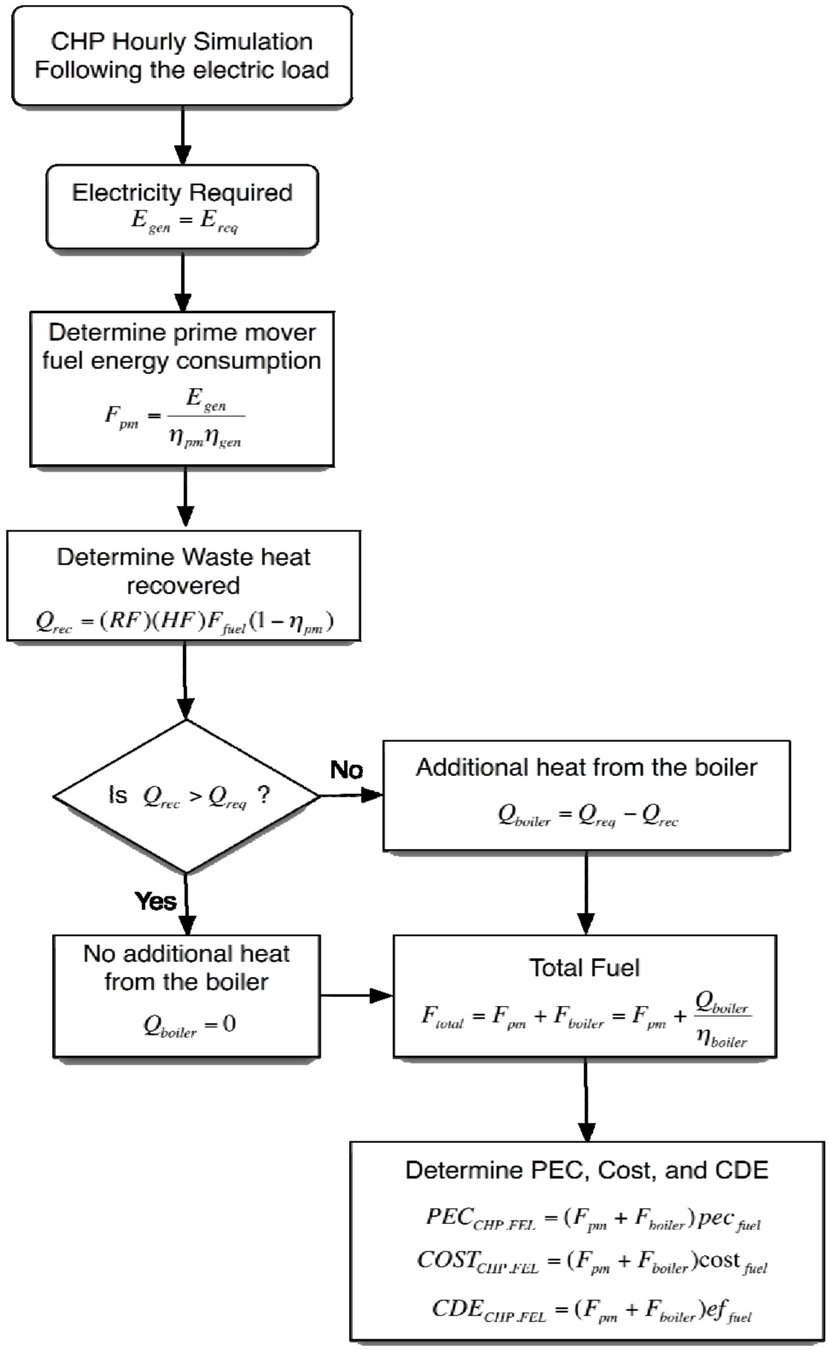


Figure 2.2 Flowchart of the Simulation of CHP-FEL

2.3 CHP System Model Following the Thermal Load (CHP-FTL)

For this operation mode, the total heat that must be recovered from the prime mover has to be equal to the thermal energy required to handle the heating load. Therefore,

$$Q_{rec} = Q_{req} \tag{2.13}$$

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

$$F_{pm} = \frac{Q_{rec}}{RF \quad \xi_{HX} \quad 1-\eta_{pm}} \tag{2.14}$$

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

$$E_{pgu} = F_{pm}\eta_{pm}\eta_{gen} \tag{2.15}$$

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

$$\text{If } E_{pgu} \quad E_{building} \quad E_c \rightarrow E_{grid} = E_{building} \quad E_c - E_{pgu} \tag{2.16}$$

$$\text{If } E_{pgu} > E_{building} \quad E_c \rightarrow E_{excess} = E_{pgu} - E_{building} \quad E_c \tag{2.17}$$

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

For this case the system may have excess electricity that could be stored or sold back to the grid. Therefore, some additional primary energy and cost savings could be estimated in this case.

The cost of the thermal load following cogeneration system is defined as:

$$COST_{CHP.FTL} = (F_{pm})\text{cost}_{fuel} \quad (E_{grid})\text{cost}_{elec} \tag{2.18}$$

The amount of primary energy consumed by the thermal load following system is shown by:

$$PEC_{CHP.FTL} = (F_{pm})pec_{fuel} \quad (E_{grid})pec_{grid} \tag{2.19}$$

where pec_{grid} is the site-to-source energy conversion factors for electricity.

The carbon dioxide emissions produced by the system is shown as:

$$\mathrm{C}DE_{CHP.FTL} = (F_{pm})ef_{fuel} \quad (E_{grid})ef_{grid} \tag{2.20}$$

where ef_{grid} is the emission conversion factors for electricity.

A flow chart of the model for CHP operation following the thermal load is presented in Figure 2.3.

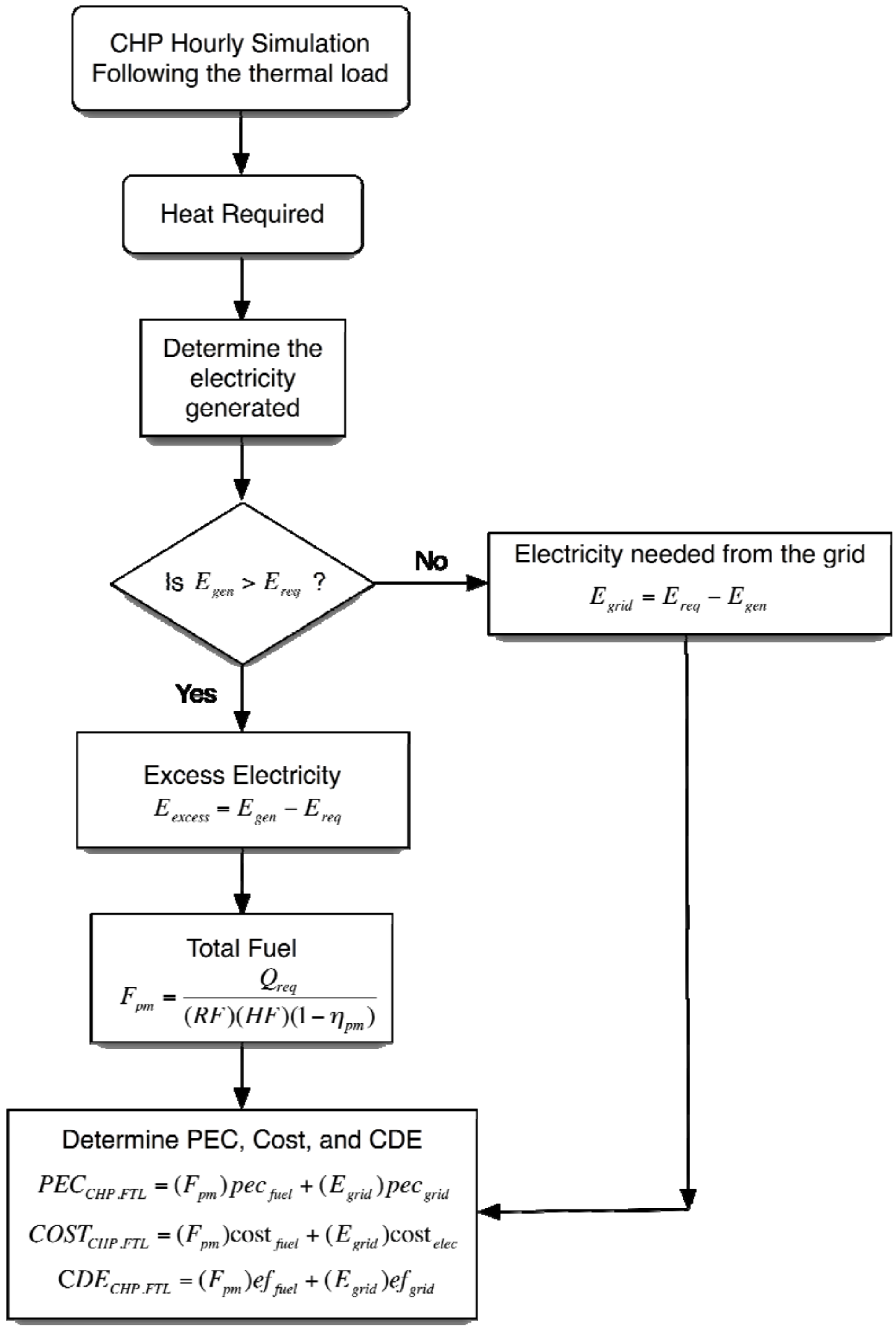


Figure 2.3 Flowchart of the Simulation of CHP-FTL

2.4 CHP System Model Following a Hybrid Electric/Thermal Load (CHP-FHL)

One of the challenges of CHP applications is the matching of thermal and electrical loads. CHP systems operate at peak efficiency when the thermal and electrical loads are well-matched. For CHP systems FEL and FTL, the least attractive times of operation occur when large amounts of excess heat and electricity are produced respectively. If the prime mover operates in the optimum mode depending on the electric and thermal load at any given time, the CHP system would be much more effective. Therefore, an optimized mode of operation following a hybrid electric/thermal load would be more effective than operating the system FEL or FTL.

The electricity generated by the CHP system can be found as a function of the heat recovered, and system component efficiencies using Equations (2.21) and (2.22) as follows

$$E_{gen} = \frac{\eta_{pm}\eta_{gen}}{(RF)(HXF)(1-\eta_{pm})}Q_{rec} \tag{2.21}$$

Since the term $\frac{\eta_{pm}\eta_{gen}}{(RF)(HXF)(1-\eta_{pm})}$ is comprised only of constants, it is simpler to refer to this term as a new constant, K:

$$K = \frac{\eta_{pm}\eta_{gen}}{(RF)(HXF)(1-\eta_{pm})} \tag{2.22}$$

With this constant defined, Equation (2.21) can be reduced to:

$$\begin{aligned} E_{gen} &= (K)Q_{rec} \\ Q_{rec} &= \frac{E_{gen}}{K} \end{aligned} \tag{2.23}$$

It is evident from Equation (2.23) that the power generated is a linear function of the heat recovered. In Figure 2.4, the bold line represents a perfect match between thermal and electrical loads found using Equation (2.23).

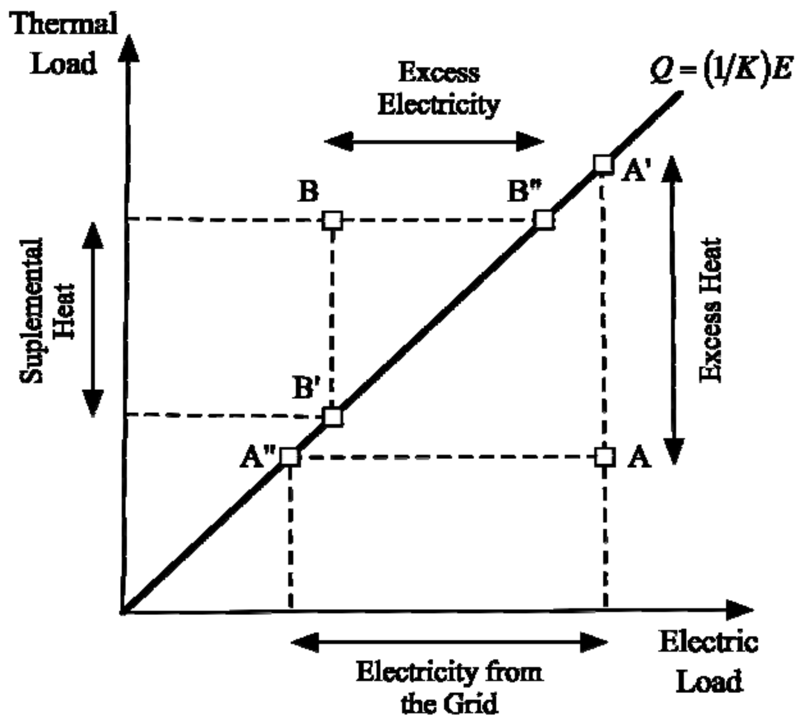


Figure 2.4 Loading Regime Chart

Because of the fluctuating nature of building loads, the times when this operational line can be achieved are extremely rare. For that reason, a design must be optimized to operate following this line. In Figure 2.4, Points A and B are typical cases of CHP operation. For the first case (Point A), if the CHP system operates FEL, it would operate at Point A′ meeting the electric load but exceeding the thermal load. However, if the CHP system runs FTL, the system would operate at Point A″ meeting the thermal load, but not the electrical load. For this case additional electricity has to be imported from the grid to satisfy the electric load. On the other hand, for Point B, if the CHP system operates FTL, it would operate at Point B″, meeting the thermal load but generating a significant amount of excess electricity. In this case, some form of electrical storage could be employed; usually in the form of batteries or a utility arrangement which allows excess electricity to be sold back to the electric grid (this option is not available at all locations). However, if the system operates FEL, it would operate at Point B′, meeting the electric load but the not the thermal load. In this case, additional heat from the auxiliary boiler is required to satisfy the thermal load.

It is evident that each of the operating modes will generate excess energy (thermal or electric) at certain points. Therefore, to eliminate the excess energy, an optimized CHP system operation would be one that is able to switch between the two operating modes. The energy optimized load following mode operates in FEL mode at points that fall above the line of operation and in FTL mode at points that fall below it. Using this function, the prime mover can be setup to produce only what is required by the system, thus producing no excess. For example, for Point A, using the optimize mode of operation, the system will operate at Point A′ satisfying the thermal load. However, electricity must be imported from the grid to satisfy the electric load. For Point B, using the optimize mode of operation, the system will operate at Point B′ satisfying the electric load but not the thermal load. Additional heat from the boiler has to be provided to satisfy the thermal load.

In order to understand the model for the proposed CHP operation mode, Figure 2.5 shows two points, one above (Point 1) and one below (Point 2) the optimum operation line. The equations used in the model depend on the location of the operation point.

The optimum-operating mode is then given by the following function:

$$\begin{aligned} &\text{if } E_{req} \quad (K)Q_{req} \quad (\text{Point 1}) \rightarrow FEL \\ &\text{if } E_{req} > (K)Q_{req} \quad (\text{Point 2}) \rightarrow FTL \end{aligned} \tag{2.24}$$

The electricity generated by the system can be determined as

$$\begin{aligned} &E_{gen} = E_{req} && \text{if} \quad E_{req} \quad (K)Q_{req} \quad (\text{Point 1}) \\ &E_{gen} = E \;= (K)Q_{req} && \text{if} \quad E_{req} > (K)Q_{req} \quad (\text{Point 2}) \end{aligned} \tag{2.25}$$

The heat recovered can be expressed as

$$\begin{aligned} &Q_{rec} = Q \;= \frac{E_{gen}}{K} && \text{if} \quad E_{req} \quad (K)Q_{req} \quad (\text{Point 1}) \\ &Q_{rec} = Q_{req} && \text{if} \quad E_{req} > (K)Q_{req} \quad (\text{Point 2}) \end{aligned} \tag{2.26}$$

When the $E_{req} \quad (K)Q_{req}$ (Point 1), system has to operate at Point 1′ and therefore supplementary heat needs to be added by the auxiliary boiler.

$$Q_{boiler} = Q_{req} - Q \;= Q_{req} - \frac{E_{req}}{K} \tag{2.27}$$

When the $E_{req} > (K)Q_{req}$ (Point 2), the system has to operate at Point 2′ and therefore additional electricity needs to be purchased from the grid. This electric power is given as:

$$E_{grid} = E_{req} - (K)Q_{req} = E_{req} - (K)Q_{req} \tag{2.28}$$

The total amount of fuel energy required by the hybrid operational mode can be determined as

$$
\begin{aligned}
F_{total} &= F_{pm} = \frac{E_{gen}}{\eta_{pm}\eta_{gen}} && \text{if} \quad E_{req} > (K)Q_{req} \\
F_{total} &= F_{pm} \quad F_{boiler} = \frac{E_{gen}}{\eta_{pm}\eta_{gen}} \quad \frac{Q_{boiler}}{\eta_{boiler}} && \text{if} \quad E_{req} \quad (K)Q_{req}
\end{aligned}
\tag{2.29}
$$

The cost of operating the system in the hybrid mode is defined as:

$$COST_{CHP.FHL} = (F_{pm} \quad F_{boiler})\text{cost}_{fuel} \quad (E_{grid})\text{cost}_{elec} \tag{2.30}$$

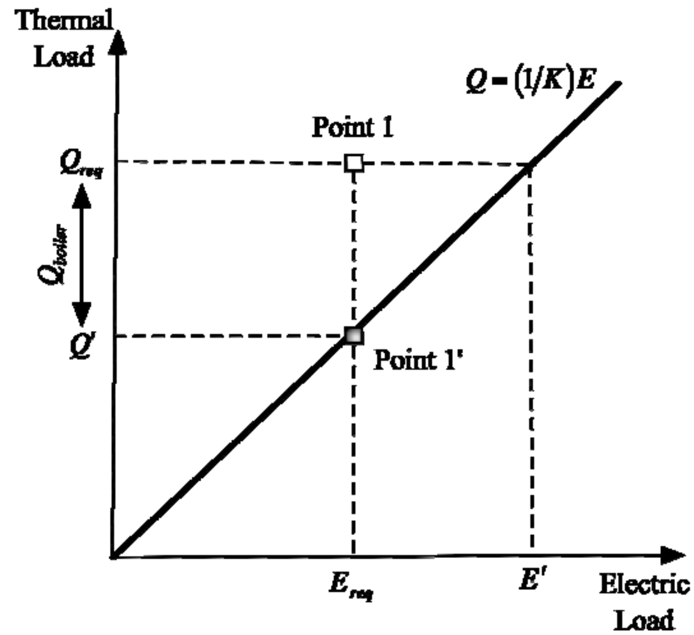
The primary energy consumed by the hybrid mode is

$$PEC_{CHP.FHL} = (F_{pm} \quad F_{boiler})pec_{fuel} \quad (E_{grid})pec_{grid} \tag{2.31}$$

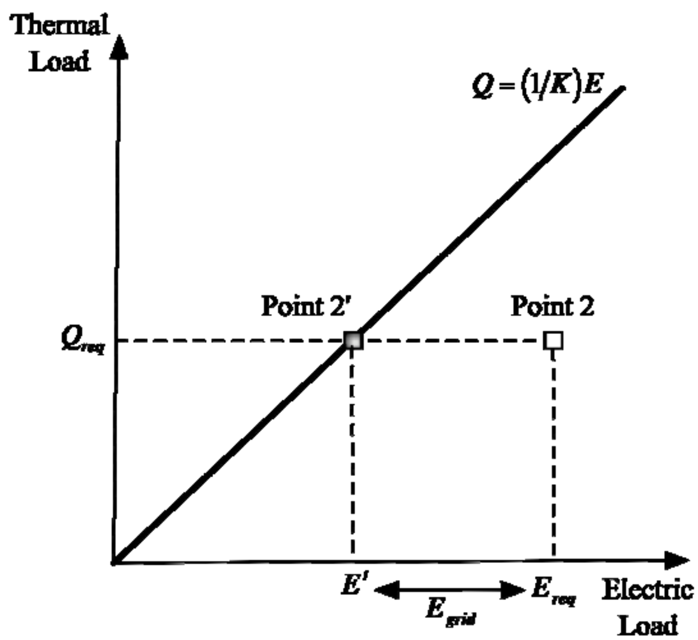
The carbon dioxide emissions produced when running in hybrid mode can be calculated as

$$CO2_{CHP.FHL} = (F_{pm} \quad F_{boiler})ef_{fuel} \quad (F_{grid})ef_{grid} \tag{2.32}$$

A flowchart illustrating CHP operation following the hybrid load is found in Figure 2.6.



(a)



(b)

Figure 2.5 FTL versus FEL Showing the CHP Optimum Operation Line

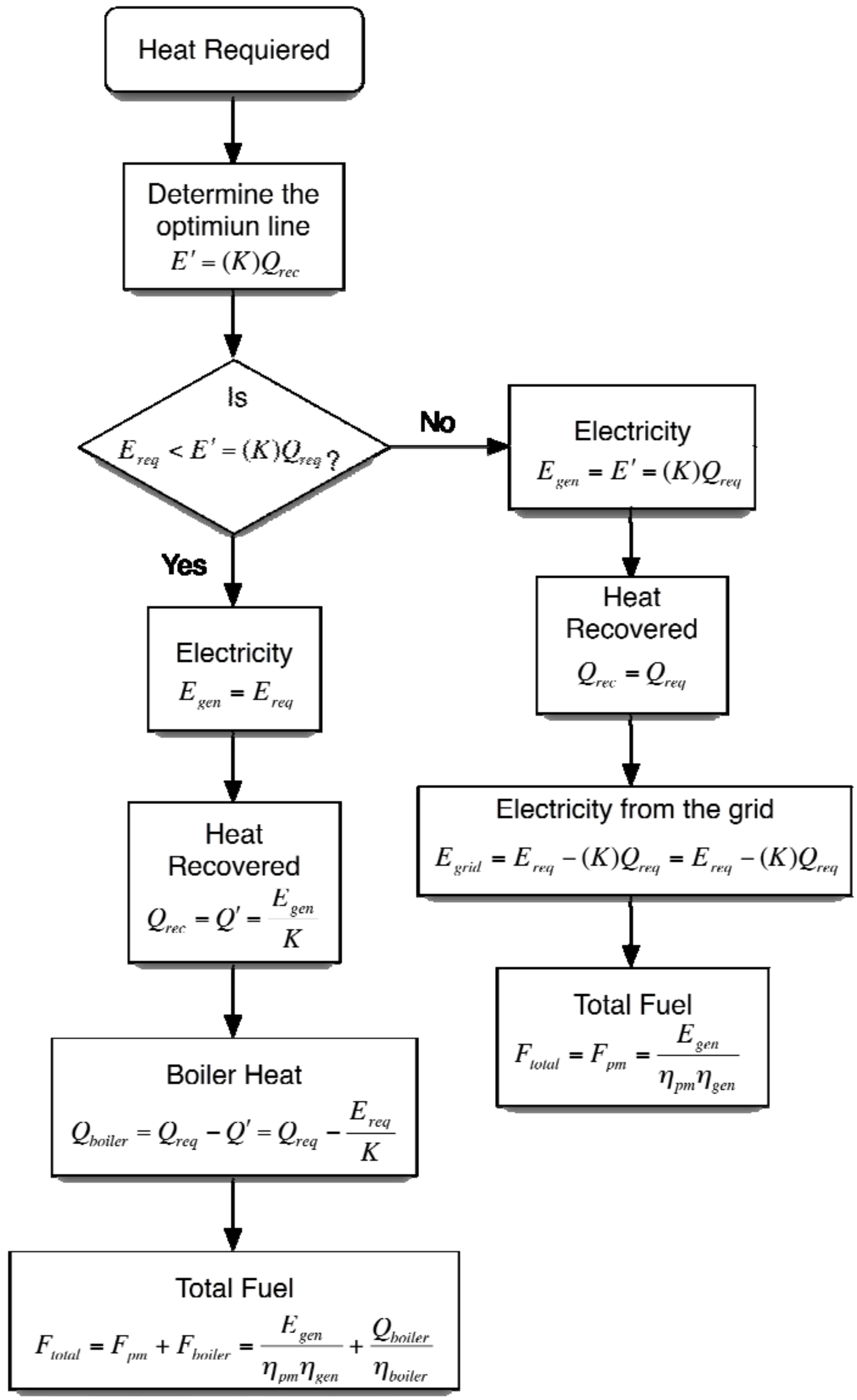


Figure 2.6 Flowchart of the Simulation of CHP-FHL

2.5 Conventional System Model

In order to quantify the difference employing a CHP system makes, a reference case is used. This case uses the electric grid to supply the entire electric load, and it uses a boiler to supply the entire thermal load. For the reference case, the PEC, cost, and emission of pollutants are determined as follows:

$$COST_{REF} = (\frac{\dot{Q}_{req}}{\eta_{boiler}})\cos t_{fuel} \quad (\dot{E}_{req})\cos t_{elec} \tag{2.33}$$

$$PEC_{REF} = (\frac{\dot{Q}_{req}}{\eta_{boiler}})pec_{fuel} \quad (\dot{E}_{req})pec_{elec} \tag{2.34}$$

$$CO2_{REF} = (\frac{\dot{Q}_{req}}{\eta_{boiler}})ef_{fuel} \quad (\dot{E}_{req})ef_{elec} \tag{2.35}$$

CHAPTER 3

RESULTS AND DISCUSSION

This section presents the results obtained from the models described in Chapter 3. A reference building was defined to compare the primary energy consumption, cost, and emission of pollutants for the different modes of operation for the propane fueled CHP system analyzed in this investigation.

3.1. Building, Region, and System Description

The reference building comprised of a normal vapor compression cycle for cooling, grid power for electricity, and a propane boiler for heating. The reference building was simulated using the software EnergyPlus [48] to obtain hourly site energy consumption data. General description of the building is presented in Table 3.1. In the definition of the CHP system, there are certain variables that must be defined in order to describe the system. These system variables are shown in Table 3.2.

Table 3.1

General Description of the Simulated Building

Building type	Retail	
Total Floor Area	5000 sq. ft	
Window-wall ratio	*North wall*	50%
	All Others	0%
Lighting	7478W	
Other Equipment	1250W	
Occupancy	17 People	

Table 3.2

Input Values for CHP System Simulation Program

Variable	Symbol	Value
Prime Mover Efficiency	η_{pm}	0.25
Generator Efficiency	η_{gen}	0.95
Boiler Efficiency	η_{boiler}	0.9
Recovery Factor	RF	0.7
Heat Exchanger Effectiveness	ξ_{HX}	0.85

Since the energy consumption profile of a building is highly dependent on the climate conditions, one city from each of the United States climate zones shown in Figure 3.1 was selected to evaluate the different operation modes. These cities are: New Orleans, LA; Boston, MA; San Francisco, CA; St. Louis, MO; and Minneapolis, MN. The price of fuels, price of electricity, and the amount of carbon dioxide emissions from the grid also varies with location. For each of the selected cities the CHP system is evaluated based on operating cost, primary energy consumption, and carbon dioxide emissions.

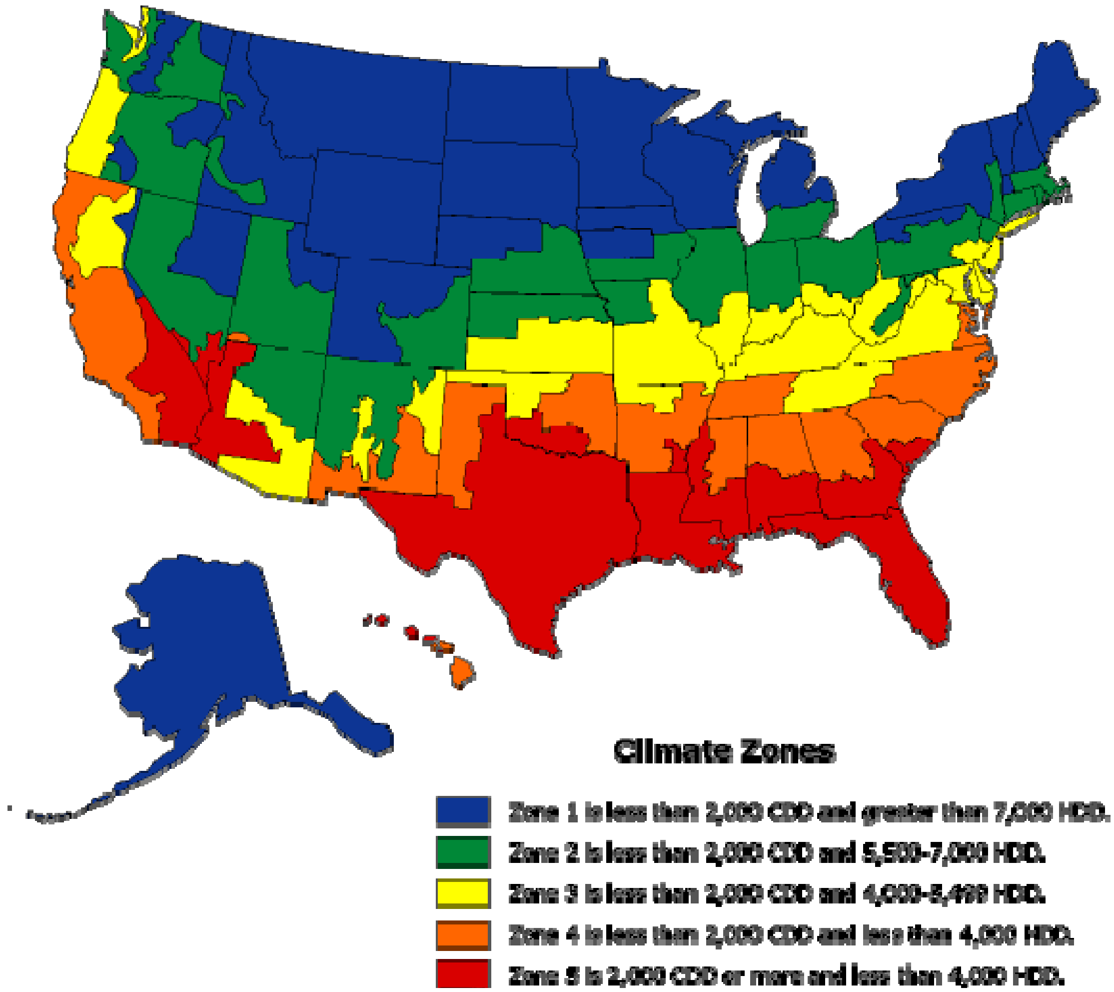


Figure 3.1 United States Climate Zones [49]

3.2. Primary Energy Consumption (PEC) and Cost Comparison

This section presents a comparison of the PEC and cost for the different modes of operation. PEC is a measure of the total energy used by a system including the energy required for fuel production. In order to find PEC, the site to source energy ratio for each energy source must be known. The site to source ratios for electricity and propane used in this investigation are shown in Table 3.3. Table 3.4 shows the values used to determine the total cost of operation for the different systems and operation modes. Figures 3.2 and 3.3 show the variation of the PEC and cost with respect to the reference case, for the different modes of operation for the evaluated cities. It is important to mention here that in both figures, a negative number implies reduction while a positive number implies increase.

Table 3.3

Site-to-Source Ratios

Energy Source	Conversion Factor [**50**]
Electricity	3.336
Propane	1.01

Table 3.4

Energy Cost by Location [50]

Zone	City	Electricity Price* (per kWh)	Propane Price* (per MBTU)
Zone 1	*Minneapolis, MN*	$0.063	$15.44
Zone 2	*Boston, MA*	$0.108	$15.89
Zone 3	*St. Louis, MO*	$0.060	$15.44
Zone 4	*San Francisco, CA*	$0.119	$15.67
Zone 5	*New Orleans, LA*	$0.074	$15.99

* Prices were taken from TargetFinder on September 20, 2008

The CHP system showed considerable reduction in PEC in some instances and sizable increases for other instances. In general, Figure 3.2 demonstrates that CHP-FTL gives mixed results for all of the cities while CHP-FEL increases PEC for all cities.

However, the proposed optimized operation mode, CHP-FHL, decreases PEC for all of the test cities. The results for CHP-FEL show that the highest PEC increase is obtained for New Orleans while the lowest is obtained for Minneapolis. Therefore, for this mode of operation, since the cooling is provided by a vapor compression system, more primary energy is consumed for the cities that required more cooling during the year. For CHP-FHL the highest PEC reduction is obtained for Minneapolis followed by Boston while the lowest is obtained for New Orleans. Therefore, the results suggest that more PEC reduction is achieved for cities that required more heating during the year. CHP-FTL reduces the PEC for San Francisco, New Orleans, and increases the Boston, Minneapolis, and St. Louis. Therefore, this mode of operation seems to be more beneficial for cities with low heating load during the year. It is important to mention that the proposed operation mode is the only on that shows reductions of PEC for all the evaluated cities.

Figure 3.3 illustrates that all operating modes in all cities have higher energy cost than the reference case when using propane as fuel. This is mainly due to the high price of propane (see Table 3.4) of all the evaluated cities. CHP-FHL gives the smallest cost increase, followed by CHP-FTL, and CHP-FEL. Interestingly, for CHP-FHL the cities with the larger heating loads, i.e. Minneapolis and St. Louis, are more costly than the cities in warmer climates. This is mainly because of the relatively low cost of electric power in these cities. For CHP-FTL and CHP-FHL mode, the warmer cities are using only grid electricity for the majority of the year, thus giving similar results to the reference case. This increase in cost should not completely rule out CHP implementation; since other parameters such as reduction of emissions may still make

CHP a viable option for this application. It is extremely difficult to compare the cost of operation for different cities since the cost of electricity and propane varies for each location.

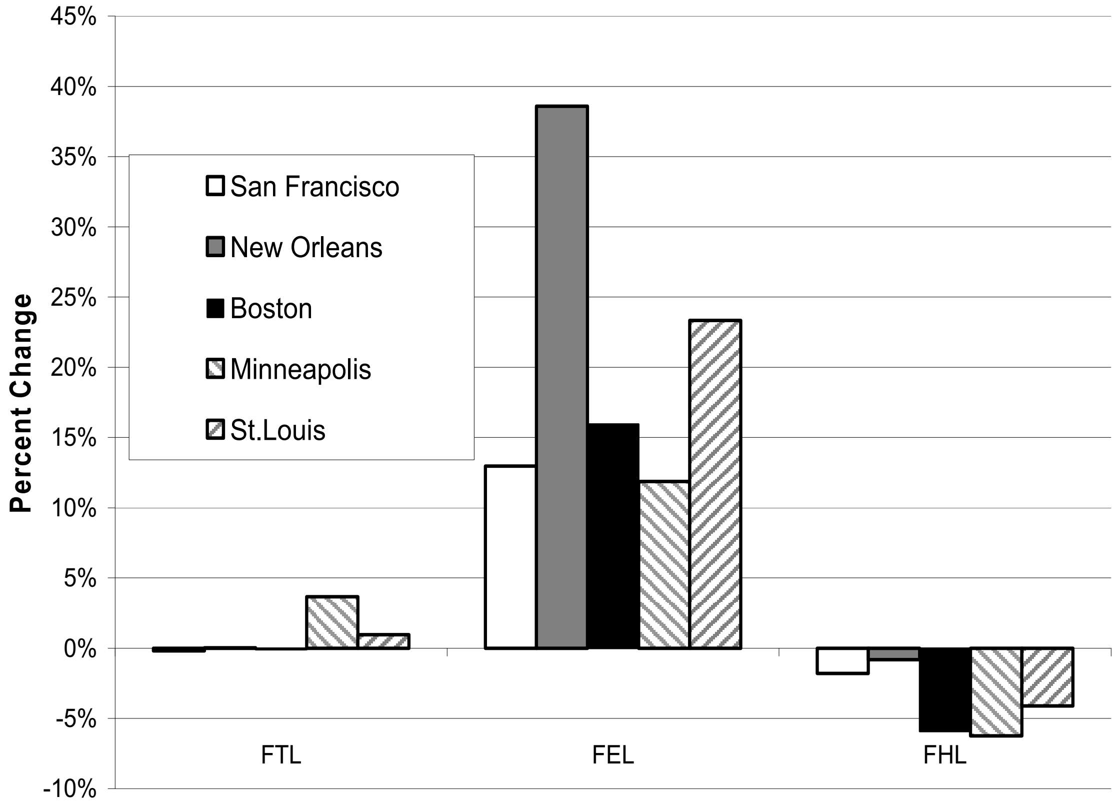


Figure 3.2 Variation of PEC for All Operating Modes

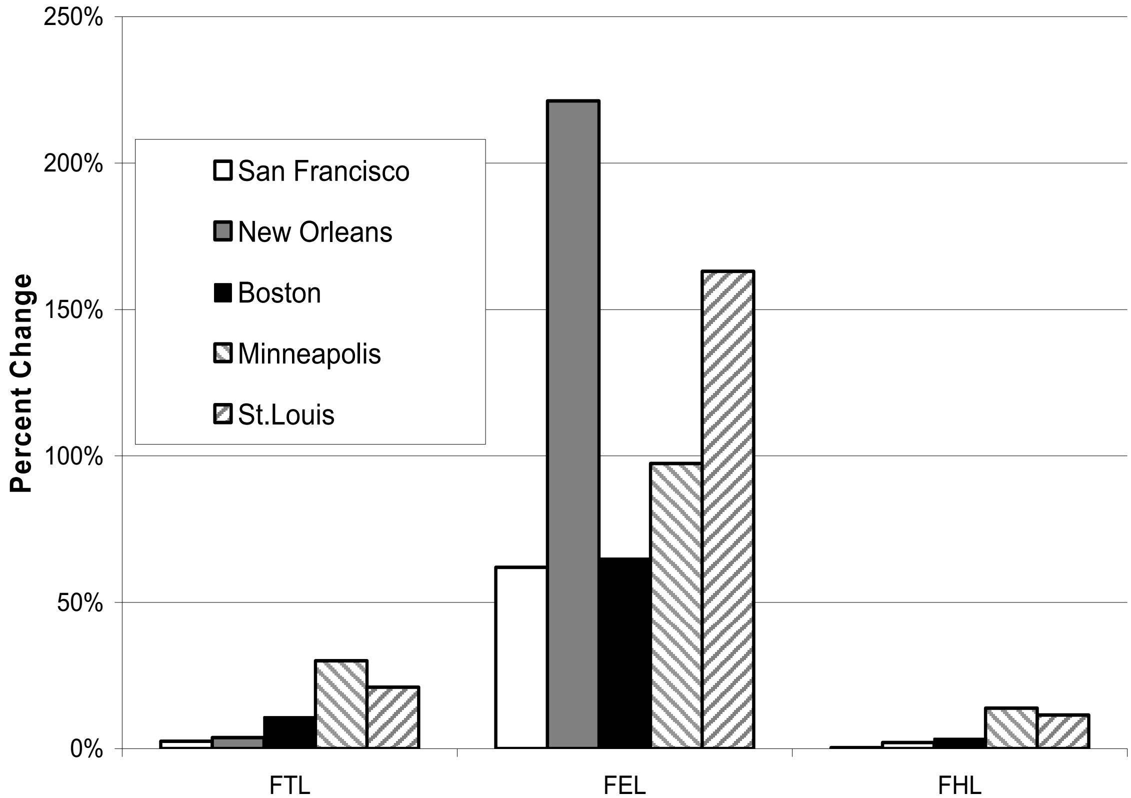


Figure 3.3 Variation of Cost for All Operating Modes

For the city of San Francisco, CHP-FHL gives the best PEC reduction, while CHP-FEL gives the largest increase. CHP-FTL reduces the PEC by 0.19% but increases the cost by 2.5%. Similarly, CHP-FHL reduces the PEC by 1.8% but increases the cost by 0.4%. However, CHP-FEL increases both the PEC and cost by 12.97% and 61.9% respectively. These results show that from an energetic standpoint, there are two viable options for CHP operating mode in San Francisco. For the city of San Francisco, the smallest cost increase is incurred for CHP-FHL, and the largest increase occurs CHP-

FEL. The actual increase is $149.5 for CHP-FTL, $3,653.9 for CHP-FEL, and $24 for CHP-FHL. The rise for CHP-FTL and CHP-FHL are small, and may be offset by lowered PEC and emissions of pollutants. However, CHP-FTL operation produces an excess of electricity (1,633 kWh/year) that could be sold back to the grid or that could be stored for future use. If this were considered into the cost analysis, the numbers would look better than the ones presented in Figure 3.3. In addition, using this excess electricity in another application indirectly would reduce the PEC by 3%. The increase for CHP-FEL is too high to implement CHP usage in this mode in San Francisco. The high cost is understandable since there is a large cooling load in the summer months in this city; causing that a big portion of the heat generated by the system not being used.

For the city of New Orleans, CHP-FHL again gives the best results for PEC reduction while CHP-FEL is the worst. For this city, the results of the cost comparison are similar to the results for San Francisco, except that CHP-FEL is even more costly. CHP-FTL slightly increases the PEC by 0.04% and increases the cost by 3.8%. For this case there is an excess of electricity of 1034 kWh/year, which could help reduce the PEC by 1.2%; this additional reduction would reduce the overall PEC for CHP-FTL. CHP-FEL gives a large increase of PEC (38.58%) and cost (221.1%). However, CHP-FHL slightly reduces the PEC by 82% but increase the cost by 2.1%. CHP-FHL, although only gives a small energy reduction is still a good operating mode for New Orleans. The extreme increase in cost for CHP-FEL is once again due to high cooling needs in the summer, which is supplied by a vapor compression system. Since the cooling load is greater in New Orleans than in San Francisco, it is clear that the cost would be even higher. The actual increase for each operation mode is $175.7 for CHP-FTL, $10,154.2 for

CHP-FEL, and $97.3 for CHP-FHL. As in San Francisco, CHP-FHL is still feasible since the cost increase is minimal but slightly reducing the PEC.

In Boston, CHP-FHL is the best operating mode for PEC reduction while CHP-FEL is the worst. In general, this city gives a larger cost increase, mostly due to slightly higher propane prices in the region. CHP-FTL and CHP-FHL reduce the PEC by 0.1% and 5.91%, respectively. However, both operation modes, CHP-FTL and CHP-FHL, increase the cost by 10.8% and 3.4%, respectively. For CHP-FTL, there is an excess of electricity of 7,334 kWh/year, which could help reducing the PEC by an additional 8.41%. CHP-FEL raises PEC by 15.96% and increases the cost by 65%. The actual cost increase for all operation modes are: $841.37 for CHP-FTL, $5,043.15 for CHP-FEL, and $265.5 for CHP-FHL. Once again, CHP-FEL is not a good option for operating mode for this city. On the other hand, CHP-FTL and CHP-FHL are viable options since they reduce the PEC with some increase in cost.

Minneapolis has a PEC reduction only for CHP-FHL while CHP-FTL and CHP-FEL give significant increase. CHP-FHL reduces PEC by 6.24% while increasing the cost by 13.8%. CHP-FTL and CHP-FEL increase PEC by 3.67% and 11.87% respectively, and the cost by 30% and 97.4%, respectively. The excess of electricity available for this case is 13,381 kWh/year, which can help reduce the PEC by 9.54%. For Minneapolis, CHP-FHL gives a good PEC reduction making it a viable operating mode for this city. As seen for the preceding cities, CHP-FEL is still not a viable operating mode with costs of $6,793 higher than the reference. CHP-FTL and CHP-FHL give even higher cost increase than in other cities, which can be attributed to the very low cost of electric power in this region. The most cost effective operating mode is CHP-FHL which gives a total increase of $966 over the reference. The cost of propane fuelled CHP systems may not be a viable option in a region with such low electricity costs.

For the city of St. Louis, CHP-FHL reduces PEC in CHP-FHL reduced the PEC by 4.1% while increasing the cost by 11.6%. The CHP-FEL increases both the PEC and cost by 23.3% and 163%, respectively. Similarly, CHP-FTL increases both the PEC and cost by 1% and 21%, respectively. However, CHP-FTL operation produces an excess of electricity (6,284 kWh/year) that could be sold back to the grid or that could be stored for future use. In addition, using this excess electricity in another application indirectly would reduce the PEC by an additional 6.%. Once again, CHP-FHL is the best option for this city. As before, CHP-FEL will not be a good operating mode for this city since it more than doubles energy costs.

From the results, it is evident that CHP-FHL is energetically the best option for all of the evaluated cities. CHP-FTL showed to be comparable to the reference case, but it did not give much PEC reduction. On the other hand, CHP-FEL gives a significant increase for each case, therefore this is not an attractive operating mode for PEC reduction. Considering the cost of Propane, the financial effect is not advantageous to the employment of Propane fuelled CHP systems. Even though CHP-FTL and CHP-FHL give only minimal cost increases for many cities, they still increase cost when compared to the reference case.

3.3. Carbon Dioxide Emissions (CDE) Comparison

The total carbon dioxide emissions produced per year was estimated for the different cities and operation modes. The calculation of carbon dioxide emission (CDE) is dependent upon the amount of emissions given off by each energy source. The amount of carbon dioxide given off per unit of energy consumed is called the emission factor. The emission factors for the evaluated cities used for this model are shown in Table 3.4. The amount of emissions factor for the electric grid changes is different for each location while for the fuel (propane) is the same for all the evaluate cities. Since the emission conversion factor for electricity is not the same for all the cities, substituting electricity by natural gas is not always beneficial for all locations in terms of emissions. For example, in St. Louis it would be beneficial due to its high emissions conversion factor for electricity. The opposite occurs in San Francisco since it has the lowest emission factors for electricity.

Table 3.5

Carbon Dioxide Emission Factors by Location [50]

City		**Grid Emission factor [(lb/kBTU)**	**Propane (lb/kBTU)**
Zone 1	*Minneapolis, MN*	0.532	0.13830
Zone 2	*Boston, MA*	0.266	0.13830
Zone 3	*St. Louis, MO*	0.540	0.13830
Zone 4	*San Francisco, CA*	0.258	0.13830
Zone 5	*New Orleans, LA*	0.330	0.13830

The results of the CDE comparison varied greatly with location. Cities with low grid emission factors benefited little with CHP implementation, while cities with high grid emission factors showed CDE reduction. The results of the CDE comparison are shown in Figure 3.4.

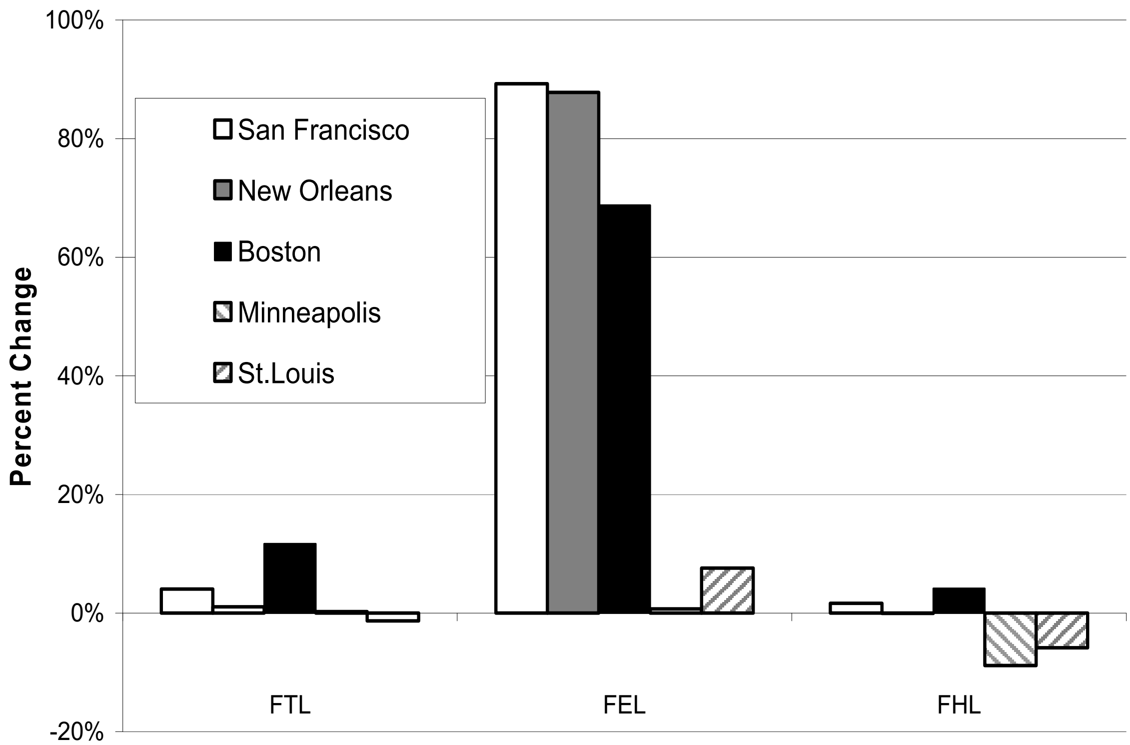


Figure 3.4 Variation of CDE for All Operating Modes

San Francisco showed an increase in CDE with CHP usage for all operating modes. CHP-FEL gave the largest increase while CHP-FHL gave the smallest. CHP-FTL increased CDE by 4.03%, CHP-FEL by 89.24%, and CHP-FHL by 1.64%.

Since San Francisco presents a low emissions conversion factor for electricity (0.258 lb/kBTU), changing electricity for natural gas produces more carbon dioxide emissions for this specific region. On an emissions basis, all CHP modes increase CDE, but CHP-FHL gives the minimal increase.

New Orleans showed a large increase in CDE in CHP-FEL, but emissions were nearly unchanged for CHP-FTL and CHP-FHL. CHP-FTL and CHP-FEL increase CDE by 1.04% and 87.8%, respectively. However, CHP-FHL gave a reduction of 0.1%, which means that the CHP-FHL system would emit almost the same as the reference case. This is also due to the relatively small emission conversion factor for electricity for this city.

Boston has one of the lowest emission conversion factor for electricity. Therefore it is understandable that none of the operating modes reduce CDE. The CDE increases for CHP-FTL, CHP-FEL, and CHP-FHL are 11.6%, 68.7%, and 4.1%, respectively. This is a typical example where changing from clean electricity to propane is not always beneficial.

Minneapolis has relatively high emission factor for electricity, making CHP usage feasible for CDE reduction. CHP-FTL and CHP-FEL are very similar to the reference case, with increases of 0.2% and 0.7% respectively. However, CHP-FHL gives a CDE reduction of 8.8%.

St. Louis has the highest emissions factor for electricity (0.532 lb/kBTU). For this reason, two of the operating modes give a reduction in CDE. CHP-FTL and CHP-FHL reduce CDE by 1.3% and 5.9%, respectively. CHP-FEL gives an increase of 7.6%, once again showing the this operation mode is not a good for this application.

The preceding sections showed the comparison of costs, PEC, and CDE of the different CHP systems operation modes and the reference case. From the results it is important to mention that a proper evaluation of the CHP system cannot be made by looking at each parameter independently of the others. In general, if CHP systems increase the cost of operation, as long as energy savings and reduction of emissions are guaranteed, the implementation of these systems should be considered.

3.4. Cost Comparison for Different Fuels

This section presents the costs of CHP systems using fuels other than Propane. Since the cost of propane fueled CHP was more than the reference case for all the operation modes, the cost of two other fuels will be investigated. CHP fuelled by Natural Gas and Diesel are evaluated because these are two common and available fuels. The prices of these fuels for each location are shown in Table 3.4; this table presents the national average price for Diesel. It is important to note that the reference case for each fuel utilizes a boiler that uses the same fuel as the proposed CHP system. It should also be noted that since the site to source ratios for Natural Gas (1.047) and Diesel (1.01) are nearly identical to Propane (1.01), then it is evident that the results of a PEC comparison would be nearly identical for all fuels. Also, the emission factor for natural gas is very similar to the emission factor for propane, but diesel has a slightly higher value of CDE. This section will neglect the slight differences in PEC and CDE for the three fuels and focus on the cost of CHP fuelled by each.

Table 3.6

Diesel and Natural Gas Cost by Location

City		Diesel Price* [49] (per MBTU)	Natural Gas Price* [50] (per MBTU)
Zone 1	*Minneapolis, MN*	$23.59	$7.87
Zone 2	*Boston, MA*	$23.59	$11.31
Zone 3	*St. Louis, MO*	$23.59	$9.48
Zone 4	*San Francisco, CA*	$23.59	$8.10
Zone 5	*New Orleans, LA*	$23.59	$8.74

* Prices were taken from TargetFinder on September 20, 2008

It is evident from Table 3.4 that the price of diesel is much higher than that of Propane. The results of the cost comparison for Diesel fuelled CHP production are shown in Figure 3.5. None of the test cities show a reduction of cost when using a diesel fuelled CHP system. The results are actually quite similar to that of the Propane fuelled CHP system. CHP-FHL is the most favorable option, and CHP-FEL gives large cost increases.

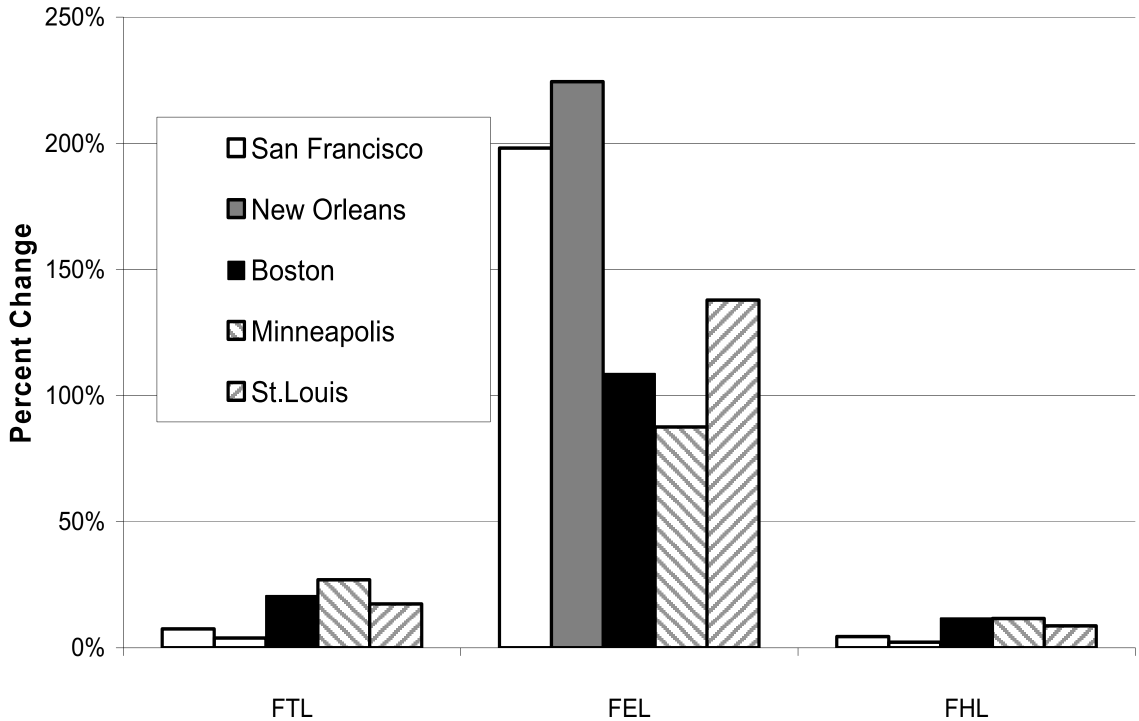


Figure 3.5 Variation of Cost for All Operating Modes Fueled by Diesel

Since the price of Natural Gas is much lower than propane and diesel in most of the evaluated cities it may be an economic advantage when using Natural Gas as a fuel. The results of the cost comparison are shown in Figure 3.6. For San Francisco natural gas as CHP fuel gives annual savings for all the operation modes. The other city that shows advantage of using natural gas is Boston, for CHP-FHL. The annual cost of CHP operation in San Francisco can be attributed to the relatively high cost of electricity and relatively low cost of natural gas for this location.

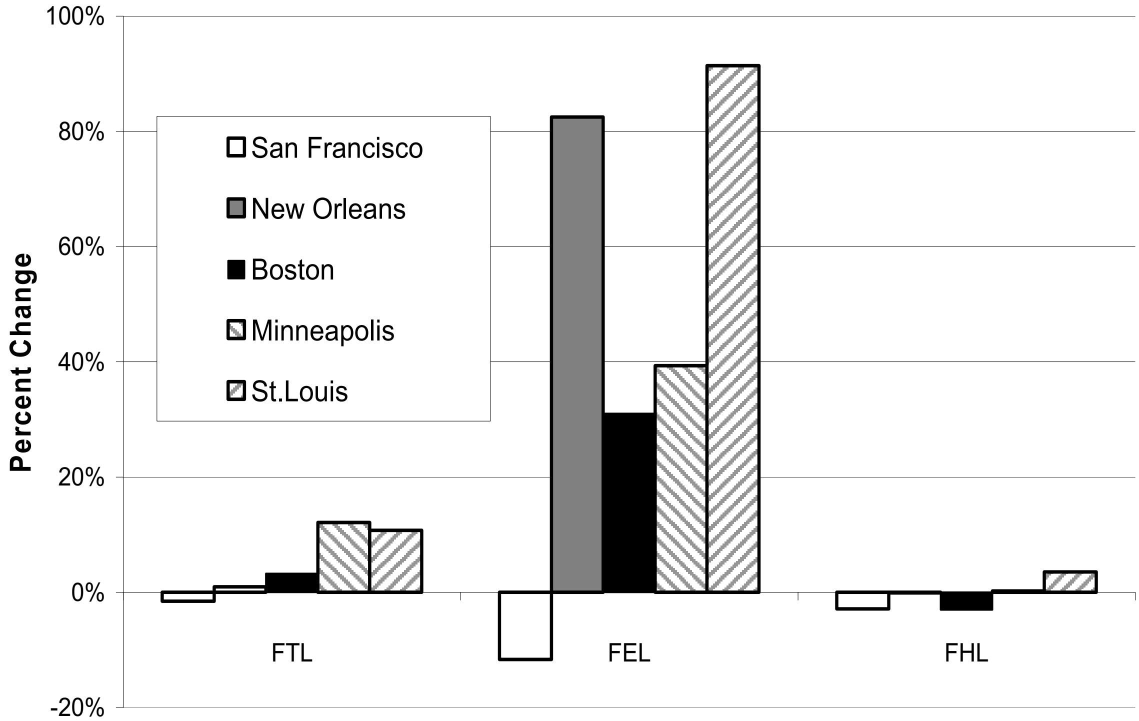


Figure 3.6 Variation of Cost for All Operating Modes Fueled by Natural Gas

3.5. CHP-FHL Monthly Comparison

This section presents a monthly comparison of the three CHP operation modes. Figure 3.7 shows the cooling, heating, and electric load for the city of Minneapolis (this city was selected for illustration purposes only). This city is the one that has the highest heating load of all the evaluated cities. Minneapolis has very large heating loads in the winter months with small cooling loads in the summer. Figure 3.8 illustrates the monthly PEC for the different operation modes.

From this figure it can be observed that the CHP-FHL operation mode approximately follows the electric load for the winter months and follows the thermal load for the summer months. This can be explained since during the winter months, the heating load is high (see Figure 3.7) Therefore following the electric load and supplement the heat needed with a boiler is more beneficial than following the thermal load and producing a great amount of excess electricity. Similarly, for the summer months, the cooling load is not that high for this city. Therefore, following the thermal load and buying electricity from the grid when needed is more beneficial than following the electric load and producing more heat than the one required for this application.

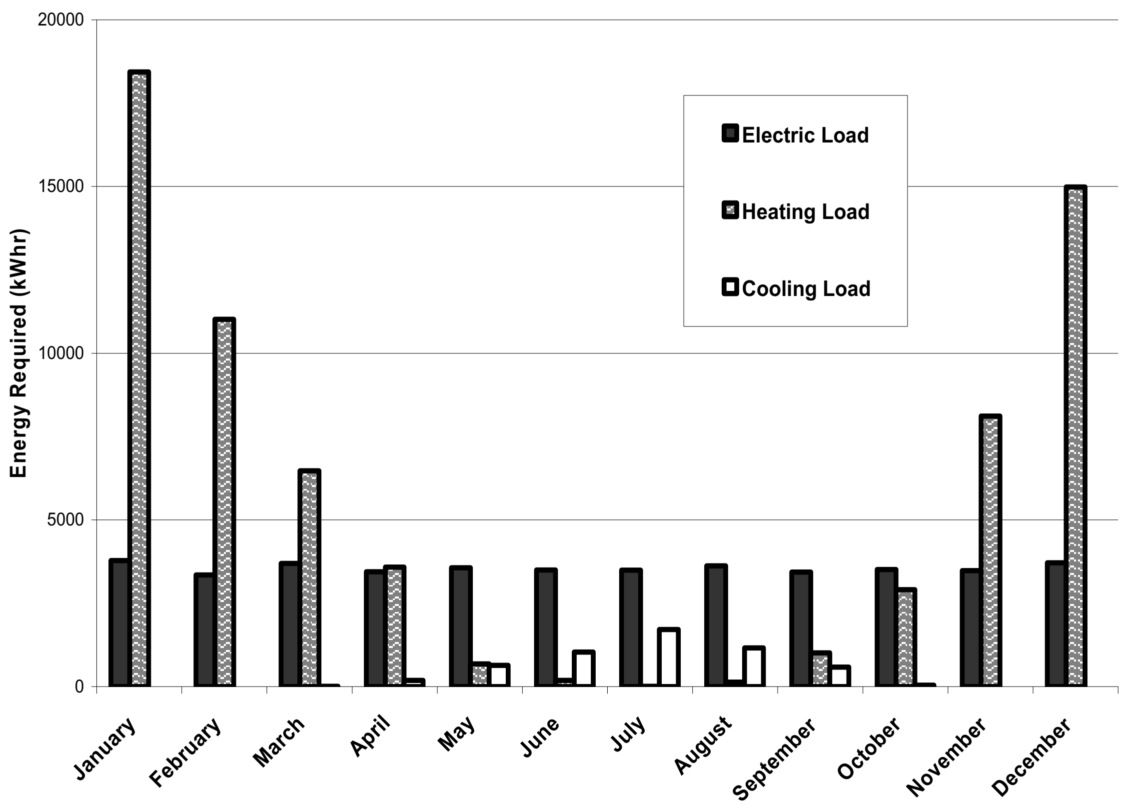


Figure 3.7 Monthly Cooling, Heating, and Electric Loads for Minneapolis

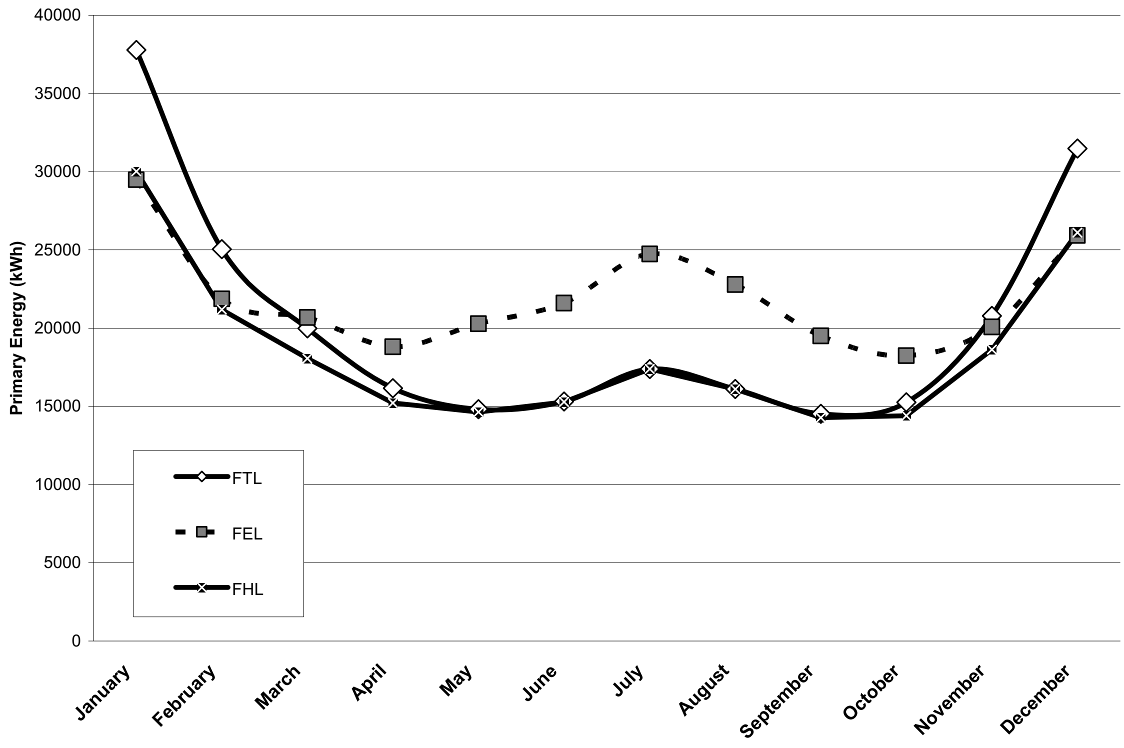


Figure 3.8 Monthly PEC for All Operating Modes in Minneapolis

Figure 3.8 clearly shows the advantage of the proposed optimized operating mode, CHP-FHL. The new mode gives the lowest primary energy consumption for each month. The ability to provide the application with the required energy in the most efficient manner shows that there is great potential for CHP-FHL.

CHAPTER 4

CONCLUSIONS

This thesis presented an evaluation of Propane fueled CHP systems based on primary energy consumption, operating costs, and carbon dioxide emissions and the comparison of these systems with conventional technologies. The methodology for the mathematical prediction of the CHP systems were presented, and the results of the prediction were studied. The feasibility of CHP applications for different climate conditions was also investigated. In addition, a new operating mode was investigated, CHP-FHL, and compared with CHP-FEL, CHP-FTL, and the conventional system. Since the propane fueled systems gave attractive results for PEC and CDE but poor results for cost, two other fuels, Natural Gas and Diesel, where evaluated based on economic considerations only.

CHP-FHL reduced PEC for all of the cities considered, while CHP-FEL increased PEC for all cities. CHP-FTL had PEC similar to the reference building for all cities except Minneapolis and St. Louis where it increased. All operating modes increased cost when using propane as a fuel. However, the proposed operation mode, CHP-FHL, gave the smallest increase. CHP-FEL gave the largest increase in cost, and CHP-FTL caused costs to rise only slightly more than CHP-FHL. CHP-FEL increased CDE for all of the cities, and FTL increased CDE in all cities except St. Louis. CHP-FHL decreased CDE in all cities except San Francisco and Boston. This is mainly because these two cities have much lower CDE from grid power than any of the other cities studied. It can be concluded that new proposed operation mode, CHP-FHL, is the best operating mode for Propane fueled CHP systems because the effects on costs, energy consumption, and emissions were much better than CHP-FEL and CHP-FTL. Although cost increases with CHP-FHL, the reduction of emissions and energy consumption show great potential for this technology. It can also be concluded that CHP-FEL is not an acceptable operating mode since it caused large increases in all three categories of interest. CHP-FTL showed little change from the conventional system in most cases, making it difficult to recommend.

It is important to mention that the prices of propane used in this investigation are the prices available for September 2008. However, if the cost of propane is lower, this technology may look more feasible, showing reduction in PEC, cost, and emissions. When other fuels are considered, it is evident that Diesel is no better than Propane when it comes to costs, due to the high Diesel prices in September 2008. Natural Gas, however, gave cost reductions in San Francisco in all operating modes and reductions in Boston for CHP-FHL. It can be concluded that Natural Gas would be economically beneficial in the two aforementioned cities.

The potential of CHP implementation is promising, with reductions in primary energy and carbon dioxide emissions attainable. Even if the cost of some systems increases with the application of CHP technology, the aforementioned reductions demand a careful consideration of this technology.

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