MICRO-COGENERATION OPTIMAL DESIGN FOR SERVICE HOT WATER THERMAL LOADS

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MICRO-COGENERATION OPTIMAL DESIGN FOR SERVICE HOT WATER

THERMAL LOADS

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LIST OF SYMBOLS

[ ]	encloses units of preceding symbol
$\$_{E,COG}$	value of electricity produced by cogenerator dail
$\$_{E,COG,M}$	value of electricity produced by cogenerator monthly
$\$_{E,COG,Y}$	value of electricity produced by cogenerator annuall
$\$_{GAS,COG}$	cost of gas consumed by cogenerator daily
$\$_{GAS,WH}$	cost of gas consumed by water heater daily
$\$_{SAV}$	net periodic savings of using cogeneration
$\$_{SAV,DAT}$	net annual savings based on electric bill data
C_{COG}	power rating specific cost of cogeneration energy system
C_E	cost of electricity
$C_{E,DAT}$	cost of electricity based on electric bill data
CER	carbon emissions reduction per da
CER_Y	carbon emissions reduction per year
C_G	cost of natural gas
$C_{P,W}$	constant-pressure specific heat of water
E_{COG}	electrical energy output of cogenerator per da
$\dot{E}_{COG,PK}$	power rating of cogenerator
$E_{COG,Y}$	electrical energy output per year of cogenerator
f(x)	probability density function

h_C	mass specific enthalpy of cold water
h_H	mass specific enthalpy of hot water
h_T	mass specific enthalpy of mixed water
HV_{GAS}	volume specific heating value of natural gas
IRRI	internal rate of return on investment
LF	load factor of cogenerator
LF_{MAX}	maximum load factor of cogenerator
m_C	mass of cold water
m_H	mass of hot water
m_T	mass of mixed water
n	number of data points
Q	thermal energy input rate
Q_{EXH}	thermal energy output of cogenerator exhaust per da
$Q_{GAS,COG}$	natural gas energy input to cogenerator per day
$Q_{GAS,WH}$	natural gas energy input to water heater per da
Q_R	energy transmitted from hot side to cool side of heat exchanger per day
RT_{MAX}	maximum daily runtime of cogenerator
SPBP	simple pay back period of cogeneration system
$SPBP_{DAT}$	simple pay back period based on electric bill data
T_C	temperature of cold water
T_H	temperature of heated water
t_m	hours of runtime per month of the cogenerator

T_T	temperature of mixed water
t_{period}	time period of interest
t_y	hours of runtime per year of the cogenerator
$V_{GAS,COG}$	volume of natural gas used by cogenerator per da
$V_{GAS,WH}$	volume of natural gas used by water heater per da
V_{NG}	volume of natural gas consumed per day
V_W	hot water volume demand per day
$V_{W,Y}$	probable annual hot water capacit
x	daily hot water usage
x_C	mass fraction of water that is cold
x_H	mass fraction of water that is hot
x_o	particular daily hot water usage
Y	cogenerator life length in years
Z	normalized hot water demand per da
$\Delta\$_{GAS,Y}$	increase in gas expenditure on cogenerator over water heater per year
ΔT_W	water temperature increase
Φ	cumulative normal distribution in days per year
$\Phi(Z)$	cumulative normal distribution in percent
Φ_o	number of days per year the hot water demand is less than or equal to x_o
η_E	gas-to-electric conversion efficiency of cogenerator
η_R	heat recovery efficienc
η_{WH}	water heater efficienc

μ_{LN} natural-log-based variance of data

ρ_W density of water

σ_{LN} natural-log-based standard deviation of data

SUMMARY

Because of advances in technology, efficient small gas turbine generators are becoming available. Simultaneously, electric utilities have become deregulated in some regions of the United States. These two factors combined encourage the decentralization of electric power generation. Decentralized power generation makes possible the recovery of the exhaust thermal energy that is a byproduct of power generation and is rejected at central power plants. Cogeneration technology is economical for facilities tha have a high uniform thermal demand, high utility electric costs, and relatively low natural gas costs. Athletic clubs display these characteristics. They have a large and fairl constant hot water demand due to their showers. Field data obtained at a health club facility shows that about 20,000 gallons of water are consumed each day. A cogeneration system was designed for such a facility, using recently introduced and currently available gas turbine equipment. This design included sizing the cogeneration system, which was accomplished by creating a statistical profile of the field data and performing an economic analysis using the cost of the equipment and the current costs of electricity and natural gas.

The study showed that an 84-kW micro-turbine generator system was appropriate for the health club facility studied. The economic and environmental impacts of that same system were then quantified. The simple pay back period in this particular case was found to be 6.8 years. After the pay back period, it was found that the facility would

continue to save $20,800 per year throughout the life of the cogenerator. The excess natural gas energy consumed by the turbine generator system over the current gas-fired water heaters results in a slight increase in on-site carbon emissions. However, the reduction in electricity provided by the central power plant results in a decrease in carbon emissions at the power plant, which far exceeds the increase at the club site. Comparing the current system with the cogeneration system, the micro-cogeneration energy syste reduces emissions by 46.7 tons of carbon per year. For a system life of 20 years, the ne result is a profit of $146.51 per ton of reduced carbon emissions. Notice this is a profit, not a cost. Studies have claimed that reducing carbon emissions costs $100-200 per ton of carbon. Those studies did not consider the new technologies that are now available.

CHAPTER I

INTRODUCTION

Cogeneration

It is normal today for a facility to depend entirely on a local electric utility for electricity. When facilities draw power from their local provider, the provider delivers electricity while throwing away thermal energy. Centralized electricity production is approximately 30% efficient. This means that 70% of that fuel energy used to generate power is rejected to river water or to the atmosphere via a cooling tower. It is not practical to transmit this thermal energy to the customer over long distances. It would be expensive and inefficient. Hence, this energy is wasted. If power sources were decentralized so that smaller plants would be near their consumers, then it can become feasible to recover that exhaust thermal energy. This is effectively what a cogeneration system does. The turbine produces electricity in a decentralized manner, being located on the property of the consumer. This makes practical the recuperation of the exhaust thermal energy via heat exchanger(s). The question remains however, is decentralized cogeneration economically feasible? If so, why are these systems not already common?

Recent changes in technology and in government regulations have changed cogeneration energy system possibilities. Micro-turbine generators have become available that are not only reasonably priced, but also competitively efficient in converting gas to electricity. Micro-turbine generators that have recently become available have gas-to-electric conversion efficiencies of 25-28%. This has not previously been the case. In government, recent legislation has deregulated the power generati industry in some locations. Previously, only regulated electric utilities were permitted to sell electricity. Now, in some states, anyone is permitted to generate electricity for their own use or to sell.

The purpose of this study is to examine the environmental effects as well as the economics of micro-cogeneration energy systems. The goal of implementing such a system would be to reduce total energy resource consumption, thereby increasing operating efficiency and reducing carbon emissions, while simultaneously economically benefiting the facility. Considered herein, a micro-cogeneration energy system consists of micro-turbine driven generator(s) and exhaust heat exchanger(s). The terms "cogeneration energy system" and "cogenerator" are used interchangeably. The micro-turbine driven generators run on natural gas and provide electricity and a high-temperature exhaust. The prefix "micro-" refers to a power rating less than about 500 kW. The heat exchangers transmit the thermal energy of the exhaust to a hot water storage tank. Switchgear is also required for connecting the system to the facility without interfering with the grid. For control, and as a safety measure in this study, electricity is drawn into a sub-circuit of the facility either from the power plant or the turbine, bu never both simultaneously.

Optimizing the Operating Strategy

A cogeneration energy system can be operated in several different ways. To find the optimal operating strategy for a facility, it is wise to compare the results of thermal, electric and economic tracking with the base case of using a gas water heater at the site and purchasing electricity from the local utility. Implementation of a cogeneration energ system can be useful to any facility with thermal and electrical needs. It can be determined for each individual facility which operating strategy is the optimum. The optimum strategy depends on how their thermal demand compares with their electrical demand. The local costs of electricity and natural gas must also be considered in the economic analysis, as well as the local taxes.

The application of a cogeneration energy system was studied at an athletic club in Atlanta, Georgia. This application was chosen because it has a very high thermal hot water demand, and the water demand from day to day is nearly constant throughout the year. It was found that an 84-kW micro-turbine generator system could meet most of the hot water demand. It was assumed that the exhaust thermal energy would be used to mee their hot water demand, as opposed to their space heating demand. An athletic club has no space heating demand in the summer, so the cogenerator would not be run. It is no economical to have costly equipment sit idle. Contrarily, the water heating demand is large throughout the year.

Sized to meet the hot water load, the turbine generator system would only produce a small percentage of a typical health club's electrical demand if it were run at full load during business hours. That being the case, the optimum operating strategy for the club would be to use the cogeneration system to meet their hot water demands and only supplement their electrical needs. This operation strategy is called “thermal tracking.” The cogenerator is run with the intent to satisfy the thermal demand of a facility, and the electricity it produces is supplemental.

“Electric tracking” describes the strategy for which a cogeneration system would be chosen to satisfy all of the electrical needs of a facility, thereby rendering the heating capability of the system supplemental. Such a facility could be completely independent o their local electric utility. For athletic clubs, that much electrical production would correspond to a thermal output much larger than what can be utilized.

In a third optimum, a system can also be designed to be operated only when it is economically beneficial to the facility using it. This is called “economic tracking.” Calculations would be performed to find an effective break-even point, i.e., at what cost of electricity does it become economically impractical to run the cogenerator? When the incremental cost of purchased electricity falls below that break-even point, the facility would not run the cogenerator. However, if the incremental cost of purchased electricity is higher than the additional cost of natural gas used to run the cogeneration energy system, it is wise to run the cogenerator.

Sometimes the most beneficial operating strategy overlaps with another. For the athletic club studied here, it turns out that it is always economical to run the cogenerator. Hence there is a 100% overlap between thermal tracking and economic tracking. However, running the cogenerator full time throughout the year exceeds the thermal load. Further, it may not be safe to run the system when the facility is closed and no staff members are on duty. Therefore, thermal tracking is taken to be the optimum for an athletic club.

Current Stud

Technical analyses are necessary to study the thermodynamic characteristics o the cogeneration energy system. This analysis is based on basic conservation of energy equations and is demonstrated in Chapter II. Conventional water heating technology is compared with the cogeneration system. An energy analysis demonstrates that 100% of the extra natural gas energy consumed by the micro-turbine generator is converted to electricity. This can be very surprising to those not familiar with the benefits o cogeneration.

An economic analysis is also necessary in order to quantify the economic benefits of cogeneration. A statistical analysis is necessary to size the cogenerator for probable hot water thermal loads. It is not practical to design the system for an assumed constant hot water load. An environmental analysis is also needed to demonstrate the effect a cogeneration system would have on carbon emissions. These analyses are carried out in Chapter III.

The two main components of the cogeneration system, the micro-turbine generator and the heat exchanger, are described in Chapter IV. The exact specifications of the micro-turbine generator selected are also mentioned in this chapter.

The operations data taken from an athletic club are discussed in Chapter V. Utility usage records were obtained and analyzed. Monthly patterns were noted of electricity and natural gas use. This chapter also reports 24 randomly selected days of daily utility usage recordings and one business day of hourly recordings.

The analyses in Chapters II and III were used and developed to predict what size cogeneration system would be ideal for the athletic club. These results are reported in Chapter VI. The net savings and pay back period of the system were also found. Further, the environmental effects of the cogenerator are noted. Both environmental and economic benefits were found. The economic benefits accounted for a sales tax of 7% in Georgia.

The different factors that affect the economic simple pay back period of the cogeneration system are noted in Chapter VII. These factors include the statistical profile of the facility's thermal demand, the size of the cogenerator, and the electric rate structur the power utility uses to bill the facility for electricity purchase. The fact that it is profitable, not costly, to reduce carbon emissions when cogeneration technology is utilized is reemphasized. Cogeneration technology is also helpful in the matter o conserving natural fuel resources. The manner in which businesses decide whether or not to invest in new equipment is considered. The effects government can have on carbon emissions reduction by deregulating utility companies and by offering incentives are discussed in this chapter. Unfortunately, many national energy and environmental strategists and business owners are not aware of the already-existing technologies tha make it possible to profitably reduce emissions. Most likely, business owners would implement cogeneration systems if they were aware of its economic benefits. Recommendations are made for future analyses that can be applied to other facilities.

CHAPTER II

THERMODYNAMIC ANALYSIS

Natural Gas-Fired Water Heater

The traditional state of the art is to obtain electricity from a central utility power provider and to heat water using a natural gas-fired water heater. Looking at the water heater (see Figure 2-1), and applying the first law of thermodynamics [6], the following equation is obtained:

$$Q_{GAS,WH} = \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_{WH}} \tag{2.1}$$

where $Q_{GAS,WH}$ is the natural gas energy input to the water heater per day η_{WH} is the efficiency of the water heater, and ρ_W, V_W, $C_{P,W}$ and ΔT_W are respectively the density volume, constant-pressure specific heat and temperature change of the hot water produced. The amount of natural gas necessary to run the water heater is related to the necessary gas energy input by the heating value of natural gas[6], HV_{GAS}:

$$Q_{GAS,WH} = HV_{GAS} \times V_{GAS,WH} \tag{2.2}$$

where $V_{GAS,WH}$ is the volume of natural gas the water heater uses per day.

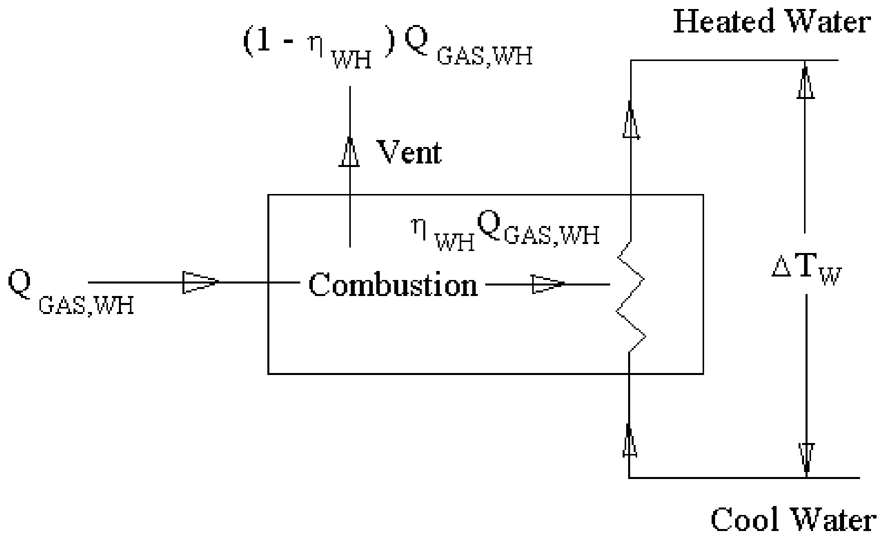

Figure 2-1: Natural Gas-Fired Water Heater Schematic

Cogeneration Energy System

The first law of thermodynamics makes it possible to derive a relationship between the amount of thermal energy needed to meet the hot water demands of a particular facility, the amount of electricity produced by the cogeneration system, and the amount of natural gas energy input to the cogeneration system

Looking only at the turbine generator (see Figure 2-2), the first law states[6]:

$$Q_{GAS,COG} = Q_{EXH} + E_{COG} \tag{2.3}$$

where $Q_{GAS,COG}$ is the energy input to the system by means of natural gas, Q_{EXH} is the thermal energy released by exhaust gases of the system and E_{COG} is the electrical energ produced by the system, all on a daily basis. Again, the amount of natural gas needed to

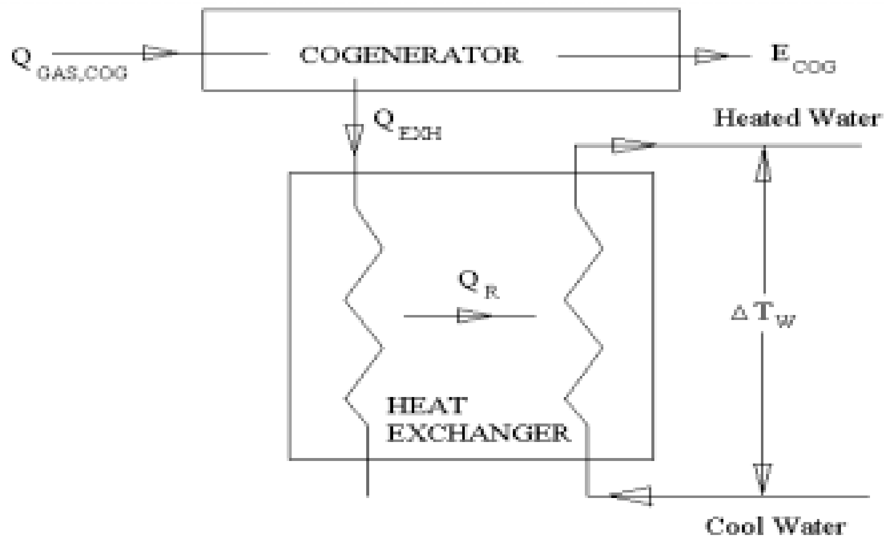

Figure 2-2: Cogeneration Energy System Schematic

run the system is related by its heating value and the gas energy input:

$$Q_{GAS,COG} = HV_{GAS} \times V_{GAS,COG} \tag{2.4}$$

where $V_{GAS,COG}$ is the volume of natural gas used by the cogenerator on a daily basis. Defining η_E as the gas-to-electric conversion efficiency of the cogeneration system,

$$E_{COG} = \eta_E Q_{GAS,COG} \tag{2.5}$$

then

$$Q_{EXH} = (1-\eta_E) Q_{GAS,COG} \tag{2.6}$$

For the hot exhaust gas side of the heat exchanger, which recovers thermal energ from the cogeneration system exhaust (see Figure 2-2), and having an exhaust hea recovery efficiency η_R:

$$Q_R = \eta_R Q_{EXH} \tag{2.7}$$

where Q_R is the amount of thermal energy that gets transmitted to the water which is being heated. Substituting equation (2.6) into equation (2.7) yields the following result:

$$Q_R = \eta_R (1-\eta_E) Q_{GAS,COG} \tag{2.8}$$

For the fluid in the cool side of the heat exchanger (see Figure 2-2), which is taken as water, the first law of thermodynamics dictates:

$$Q_R = \rho_W V_W C_{P,W} \Delta T_W \tag{2.9}$$

Note that all of these equations are still being derived on a daily basis. Hence, V_W is the volume of hot water a facility uses per day. Substituting equation (2.7) into equation (2.9) and solving for Q_{EXH} gives the following result:

$$Q_{EXH} = \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_R} \tag{2.10}$$

Substituting equation (2.6) into equation (2.10) and solving for $Q_{GAS,COG}$ gives the following:

$$Q_{GAS,COG} = \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_R (1-\eta_E)}$$

(2.11)

Solving equation (2.5) for $Q_{GAS,COG}$ and substituting it into equation (2.11) and solving for E_{COG} gives this result:

$$E_{COG} = \frac{\eta_E \rho_W V_W C_{P,W} \Delta T_W}{\eta_R (1-\eta_E)}$$

(2.12)

To find the maximum power rating of the cogenerator necessary to meet a given ho water demand of a facility, again on a daily basis, it is necessary to define a cogenerator load factor and relate it to the electrical energy output, E_{COG}, corresponding to the daily hot water demand, V_W:

$$E_{COG} = t_{period} LF \times \dot{E}_{COG,PK}$$

(2.13)

where $\dot{E}_{COG,PK}$ is the maximum power rating of the cogenerator and t_{period} is the time period of interest. The load factor, LF, is the product of two factors: the percentage o time that the cogenerator runs, and the percentage of full load at which it operates:

LF = (% time) (% full load)

(2.14)

If the cogenerator ran at 50% of full load 100% of the time, it would have the same load factor as if it ran at 100% of full load 50% of the time. It is possible that the cogenerator may operate at a different gas-to-electric conversion efficiency depending on what percentage of full load it runs, but in this study the gas-to-electric conversion efficienc was assumed to be constant. Substituting equation (2.13) into equation (2.12) and solving for $\dot{E}_{COG,PK}$ results in the following equation:

$$\dot{E}_{COG,PK} = \frac{\eta_E \rho_W V_W C_{P,W} \Delta T_W}{t_{period} LF \eta_R (1-\eta_E)}$$

(2.15)

The above equation is the relationship between the size of the cogenerator and the daily hot water produced by that cogeneration energy system.

Comparison of Cogeneration with Traditional Water Heating Technology

If it is assumed tha $\eta_{WH} = \eta_R$, then equation (2.1) only differs from equati (2.11) by the quotient (1 - η_E). This is a reasonable assumption to make because the hea transfer conditions of a water heater and an exhaust heat recovery heat exchanger are similar. Further, both run on the same fuel. Hence, for $\eta_{WH} = \eta_R$,

$$Q_{GAS,WH} = Q_{GAS,COG}(1-\eta_E)$$

(2.16a)

or

$$\begin{aligned} Q_{GAS,COG} - Q_{GAS,WH} &= Q_{GAS,COG} - Q_{GAS,COG}(1-\eta_E) \\ &= Q_{GAS,COG}(1-1+\eta_E) \\ &= \eta_E Q_{GAS,COG} \end{aligned}$$

(2.16b)

Similarly, substituting equations (2.2) and (2.4) into equation (2.16a) results in the following:

$$V_{GAS,WH} = V_{GAS,COG}(1-\eta_E)$$

(2.17a)

or

$$V_{GAS,COG} - V_{GAS,WH} = \eta_E V_{GAS,COG}$$

(2.17b)

The energy analysis below demonstrates in thermodynamic terminology how and why cogeneration energy systems are beneficial in the area of conserving energy and reducing the energy costs of a facility. An equation is derived to describe how much of the extra gas energy used by a cogenerator is converted to electricity. The ratio of the amount of gas energy used by the water heater to the amount of electrical energy the cogenerator would produce if it were used to produce a corresponding amount of hot water is found by dividing equation (2.1) by equation (2.12):

$$\frac{Q_{GAS,WH}}{E_{COG}} = \frac{\eta_R(1-\eta_E)}{\eta_{WH}\eta_E}$$

(2.18)

The ratio of the amount of gas energy the cogenerator uses to the amount of electricity it produces is found by rearranging equation (2.5):

$$\frac{Q_{GAS,COG}}{E_{COG}} = \frac{1}{\eta_E}$$

(2.19)

Subtracting equation (2.18) from equation (2.19) and substituting equations (2.1), (2.11) and (2.12) gives the ratio of the excess gas energy consumed to the electrical energ produced by the cogeneration energy system:

$$\frac{Q_{GAS,COG} - Q_{GAS,WH}}{E_{COG}} = \frac{1}{\eta_E} - \frac{\eta_R}{\eta_{WH}\eta_E} + \frac{\eta_R}{\eta_{WH}}$$

(2.20)

For the case where the efficiency of heat recovery, η_R, is equal to the efficiency of the water heater, η_{WH}, equation (2.20) simplifies as follows:

$$\frac{Q_{GAS,COG} - Q_{GAS,WH}}{E_{COG}} = \frac{1}{\eta_E} - \frac{1}{\eta_E} + 1$$

$$= 1$$

(2.21)

This means that 100% of the extra gas energy consumed by the cogenerator is converted to electricity. Contrary to a possible initial reaction, equation (2.21) does not violate the Carnot principle [6]. The equation does not state that the operating efficiency of the cogenerator is 100%. It states that exhaust heat is being recovered, not wasted. For cases where η_R does not equal η_{WH}, e.g., i η_R = 70%, η_{WH} = 80%, and η_E = 26%, then equation (2.20) states that 61% of the incremental gas energy used is converted to electricity. If η_R = 80% and η_{WH} = 70%, again wit η_E = 26%, equation (2.20) states that 59% of that energy is converted to electricity.

Water Temperature Rise

The water temperature rise and the amount of hot water consumed are closely linked. The two terms must be defined in harmony with each other, but this can be done one of two ways. The health facility can be treated as a common mixing junction (see Figure 2-3). The outlet temperature T_T is the average temperature of all the water consumed by a facility. The inlet temperature T_C is the temperature of the cold water tha comes into the club without being heated and is typically equal to the ambient temperature. The inlet temperature T_H is the temperature to which water is heated in the water heater, or in a heat exchanger. If the volume of hot water consumed is defined as only and exactly the hot water delivered by the water heater, then the temperature increase would be equal to T_H - T_C. Alternatively, if the hot water consumed is defined as the total amount of water consumed, i.e., the mixed water leaving the facility, then the temperature increase would be equal to T_T - T_C. Since the amount of cold water used at a health club facility is negligible, it was more convenient to use the latter definitions o

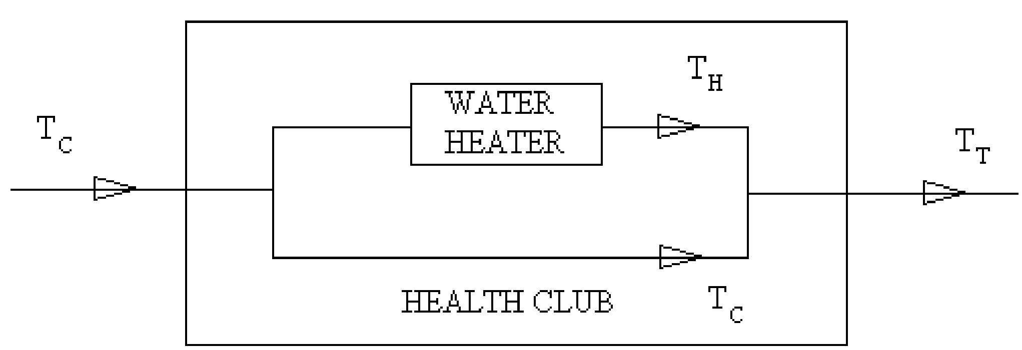

Figure 2-3: Mixing Junction Schematic

temperature rise and water volume consumed. Although all three of the above temperatures were known, it was impossible to separate the amount of hot water consumed from the amount of cold water consumed, i.e., m_T was measured, but m_C and m_H could not be measured. If m_C and m_H had been measured, T_T could be found in the following manner[6]:

$$m_C + m_H = m_T \tag{2.22a}$$

$$x_C = \frac{m_C}{m_T} \text{ and } x_H = \frac{m_H}{m_T} \tag{2.22b}$$

$$x_C + x_H = 1 \tag{2.22c}$$

$$0 = m_C(h_T - h_C) + m_H(h_T - h_H) \tag{2.23a}$$

$$0 = m_C C_{P,W}(T_T - T_C) + m_H C_{P,W}(T_T - T_H) \tag{2.23b}$$

$$0 = x_C m_T C_{P,W}(T_T - T_C) + x_H m_T C_{P,W}(T_T - T_H) \tag{2.23c}$$

$$0 = x_C(T_T - T_C) + x_H(T_T - T_H) \tag{2.24a}$$

$$T_T = x_C T_C + x_H T_H$$

(2.24b)

or,

$$T_T = (1 - x_H) T_C + x_H T_H$$

(2.24c)

The mass fractions x_C and x_H were unknown. Since most of the hot water used at the athletic club facility is shower water, T_T was assumed to be approximately 105 °F. This estimate also includes consideration for the water consumed by the clothes washers when towels are washed. The towels are washed in water heated to temperatures greater than 105 °F. The rinse cycle uses cold water. The symbol $_C$ represents the average ambien temperature in Atlanta.

CHAPTER III

ECONOMIC, PROBABILITY AND ENVIRONMENTAL ANALYSES

Economic Analysis

The previous analysis shows that a cogeneration system requires more fuel to produce the same quantity of hot water as a gas-fired water heater. This was shown in equation (2.17). The benefit in using a cogeneration system is the electricity i simultaneously produces, which a conventional water heater does not. It is logical at this point to ask does the value of the electricity produced by the cogenerator exceed the added value of the gas necessary to run it? Whether or not it is worth while to implement the cogeneration system also depends on how much capital has to be invested, and therefore, the length of the simple pay back period[15]. Defining $\$_{SAV}$ as the net periodic savings from operating the cogeneration system, this term is comprised of three components:

$$\$_{SAV} = \$_{E,COG} - \$_{GAS,COG} + \$_{GAS,WH} \tag{3.1}$$

where $\$_{E,COG}$ represents the value of the electricity produced by the cogenerator, $\$_{GAS,COG}$ represents the cost of gas spent running the cogenerator and $\$_{GAS,WH}$ represents the cost o gas saved by not using the water heater. These terms are each individually calculated b using the equations derived in the thermodynamic analysis and simply multiplying them by the cost of electricity, C_E, and cost of gas, C_G:

$$\$_{E,COG} = E_{COG} C_E \tag{3.2a}$$

$$\$_{GAS,COG} = Q_{GAS,COG} C_G \tag{3.2b}$$

$$\$_{GAS,WH} = Q_{GAS,WH} C_G \tag{3.2c}$$

Substituting equations (2.12), (2.11), and (2.1) respectively into equations (3.2), and assuming $\eta_{WH} = \eta_R$, yields the following set of equations:

$$\$_{E,COG} = C_E \frac{\eta_E \rho_W V_W C_{P,W} \Delta T_W}{\eta_R (1-\eta_E)} \tag{3.3a}$$

$$\$_{GAS,COG} = C_G \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_R (1-\eta_E)} \tag{3.3b}$$

$$\$_{GAS,WH} = C_G \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_R} \tag{3.3c}$$

Substituting equations (3.3) into equation (3.1) yields:

$$\$_{SAV} = \rho_W V_W C_{P,W} \Delta T_W \left(\frac{C_E \eta_E}{\eta_R (1-\eta_E)} + \frac{C_G}{\eta_R} - \frac{C_G}{\eta_R (1-\eta_E)} \right)$$

(3.4a)

Equation (3.4a) can be simplified to obtain the following result:

$$\$_{SAV} = \frac{\rho_W V_W C_{P,W} \Delta T_W \eta_E}{\eta_R (1-\eta_E)} \left(\frac{C_E}{C_G} - 1 \right) C_G$$

(3.4b)

Note that if V_W is water consumed on a daily basis, $\$_{SAV}$ is dollars saved on a daily basis, or with unit conversions, on an annual basis. Either way $_{SAV}$ is in units of dollars per time period. The net periodic savings can also be described as a function of the load factor. Combining equation (2.15) with equation (3.4b) gives the following relationship:

$$\$_{SAV} = t_{period} LF \times \dot{E}_{COG,PK} \left(\frac{C_E}{C_G} - 1 \right) C_G$$

(3.4c)

This equation shows that if the costs of electricity and gas are fixed, as well as the power rating of the cogenerator, then the savings increases proportionately as the load factor i increased. If the load factor is doubled, the savings is also doubled.

Equation (3.4c) can be used to find a break-even point. This is to say, at what cost of electricity does it become profitable to run the cogenerator? The first step is to set equation (3.4c) greater than zero:

$$t_{period} LF \times \dot{E}_{COG,PK} \left(\frac{C_E}{C_G} - 1 \right) C_G > 0$$

(3.5a)

This criterion can be reduced to:

$$C_E > C_G$$

(3.5b)

Note, however, that the units in equation (3.5c) could be mixed. Knowing that C_E is typically available in units of $/kW-hr and C_G in units of $/MBtu, the following conversion makes the comparison straightforward:

$$C_E\left[\frac{\$}{kW-hr}\right] > C_G\left[\frac{\$}{MBtu}\right]\frac{1}{293.1}\left[\frac{MBtu}{kW-hr}\right]$$

(3.5c)

The current cost of natural gas for a typical health facility is $3.40/MBtu, which includes delivery. The rate structure for the cost of gas is fla [2], i.e., no matter how much or how little natural gas the facility purchases it costs $3.40/MBtu. Applying that value to equation (3.5c) demonstrates that the cost of electricity must be greater than $0.0116/kW-hr in order to profit from running a cogenerator. The fuel recovery cost of electricity[7] in the electric rate structure[7] is $0.013994/kW-hr (see Appendix C). This does not include the cost of providing electric service, which varies widely depending on several factors, such as the peak electrical load. Therefore, at the rates under which gas and electricity are being purchased by the facility, it is always profitable to run the cogenerator.

The simple pay back period is directly related to the cost of the cogeneration energy system equipment divided by the net periodic savings:

$$SPBP = \frac{C_{COG} \dot{E}_{COG,PK}}{\$_{SAV}}$$

(3.6a)

The simple pay back period can also be described as a function of the load factor. Substituting equation (3.4c) into equation (3.6a) gives the following relationship:

$$SPBP = \frac{C_{COG}}{LF\left(\frac{C_E}{C_G} - 1\right)C_G}$$

(3.6b)

or

$$LF \times SPBP = \frac{C_{COG}}{\left(\frac{C_E}{C_G} - 1\right)C_G}$$

(3.6c)

It can be seen from equations (3.6b) and (3.6c) that the simple pay back period is inversely proportional to the load factor, i.e., if the load factor is doubled, the simple pay back period is halved, just as the savings is doubled. Also, if the cost of electricity is increased, the simple pay back period decreases. Figure 3-1 is a graphical presentation of equation (3.6c).

The simple pay back period does not account for the time value of money. In order to account for the time value of money, an equivalent interest rate representing inflation would have to be assumed. The simple pay back also does not account for increases in the costs of natural gas and electricity. Since these factors are both somewha unpredictable, it is better to use the simple pay back period first and then account for other factors when they are better known.

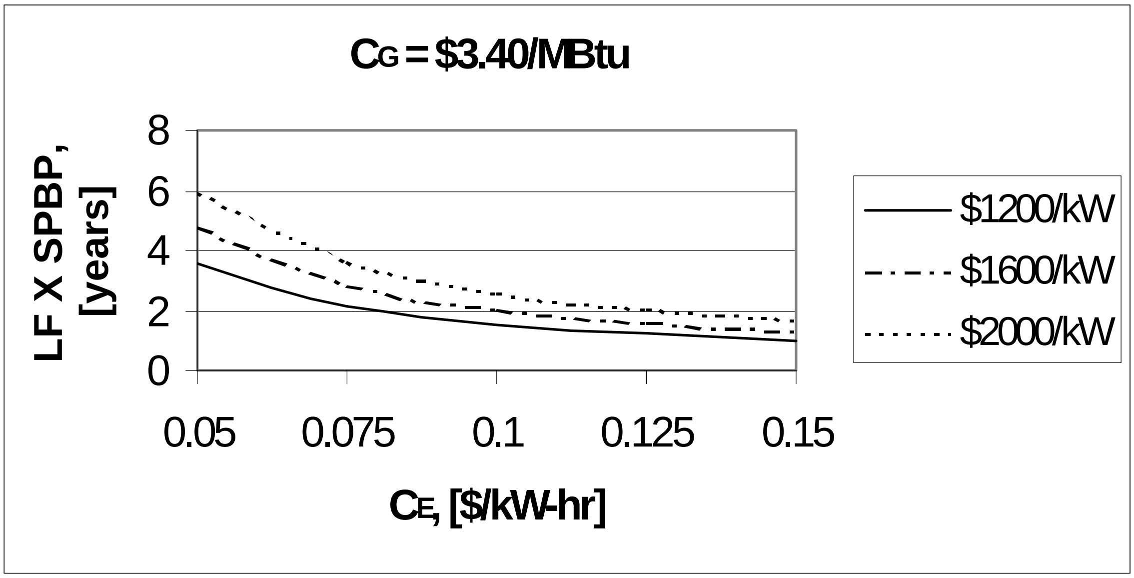

Figure 3-1: Simple Pay Back Period vs. Electrical Rate

Probability Analysis

In order to obtain a statistical distribution of a facility's hot water consumption, data must be taken and then compiled. In this study, it was necessary to use the natura logarithm of the data taken. Hence some variables have the subscript "LN" attached to them. The lognormal distributi [8] had to be used because the normal distribution woul have said that there were small probabilities that the water consumption of the facilit would be negative. In reality, that would be impossible. Contrarily, the natural logarithm of data cannot result in negative values because even when a number approaches negative infinity, the exponent of that number approaches zero. This is acceptable because on certain holidays, a facility may close for a full day and on that day their water usage would be zero.

The lognormal version of the probability density function [8] states:

$$f(x) = \frac{1}{x\sigma_{LN}\sqrt{2\pi}} \exp\left(\frac{-(\ln x - \mu_{LN})^2}{2\sigma_{LN}^2} \right)$$

(3.7)

The variable x is the hot water consumption of a facility for a given day. The variance, μ_{LN}, is the mean of the natural logarithm of the daily water consumption data taken at the facility, V_W:

$$\mu_{LN} = \frac{\sum_n \ln V_W}{n}$$

(3.8)

where n is the number of data points taken. The standard deviation, σ_{LN}, is also defined below:

$$\sigma_{LN} = \sqrt{\left(\frac{\left(n\sum_n (\ln V_W)^2 \right) - \left(\sum_n \ln V_W \right)^2}{n(n-1)} \right)}$$

(3.9)

The function f(x), plotted with the daily hot water consumption along the horizontal axis, results in a sort of bell-shaped curve, the bell becoming elongated to the right (see Figure 3-2). Hypothetical "data" was used for illustration. The hypothetical data had a natural-log-based variance of 2.45 and a natural-log-based standard deviation

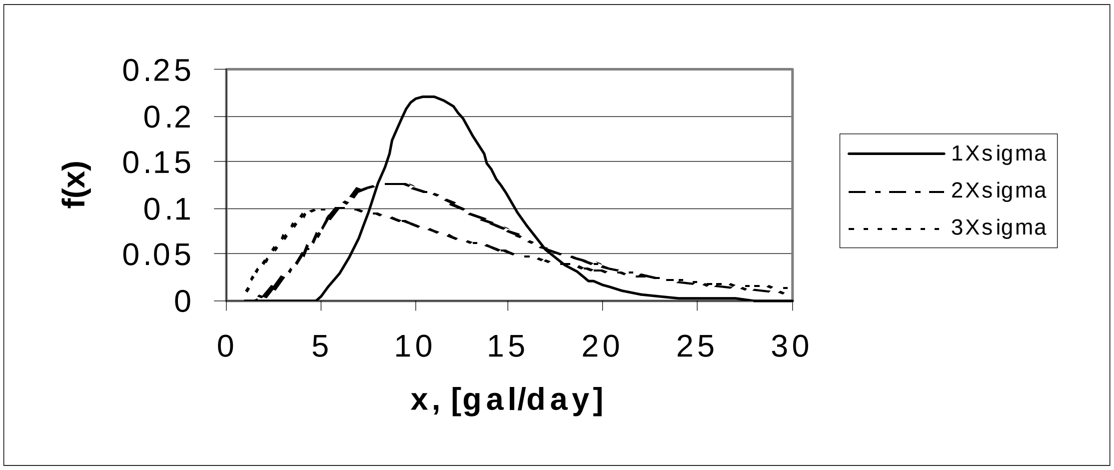

Figure 3-2: Sample Probability Density Function

of 0.274. Notice the difference in the shape of the curve when the standard deviation is doubled and then tripled. Statistical theory[8] says the probability that a normal random variable is within one standard deviation of its mean is 68%. The probability that it is within two standard deviations is 95%, and within three standard deviations 99.7%.

It is desirable t calculate the probability that the facility would use x gallons of hot water per day or less. This is directly related to the probability that a given size cogeneration system would meet 100% of the facility's hot water requirement on a given day. When this probability is multiplied by the number of days in a year, the curve would represent how many days out of the year that much water, or size cogenerator, woul meet the facility's needs (see Figure 3-3). To normalize the curve, the variable Z is defined:

$$Z = \frac{\ln x - \mu_{LN}}{\sigma_{LN}} \tag{3.10}$$

The cumulative normal distribution[8] is then defined:

$$\Phi(Z) = \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-Z^2}{2}\right)$$

(3.11)

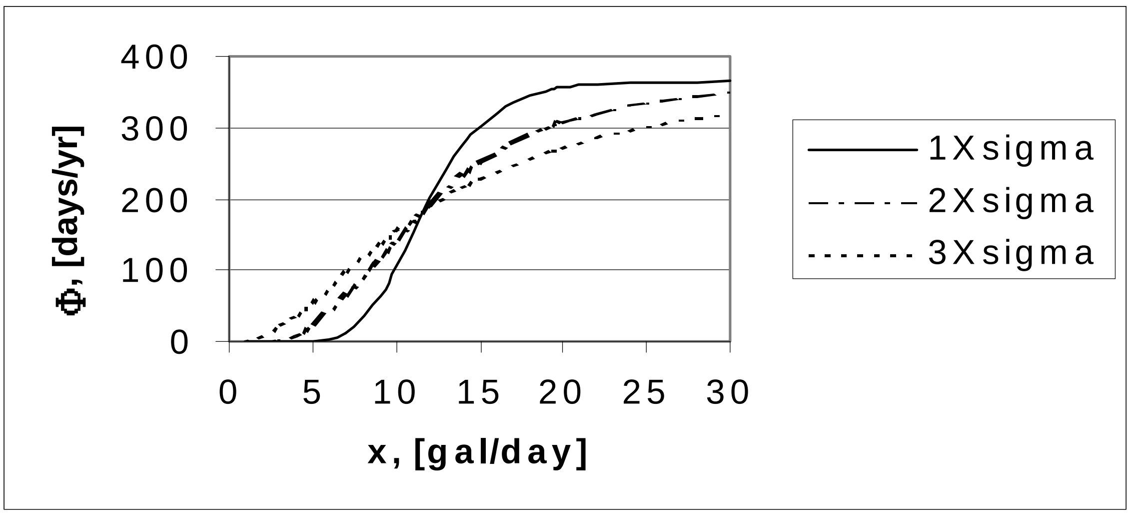

Figure 3-3: Sample Cumulative Distribution

It then becomes helpful to exchange the axes in Figure 3-3, obtaining Figure 3-4. The integral under the curve of Figure 3-4 shows the amount of hot water the cl consumes per year. The curve can be integrated by the trapezoid method[9]. Then, the maximum amount of hot water that would be produced by the cogenerator is the sum of two terms. The two terms are the integral of x over the interval of days the requirement i satisfied, 0 to Φ_o, and the product of the corresponding daily hot water usage, x_o, with the number of days left in the remainder of the year, (365 - Φ_o). The symbol x_o represents the maximum amount of hot water the cogenerator can provide on a given day. This is clarified by drawing a horizontal line from the coordinate (Φ_o, x_o) through the end of the year to the right in Figure 3-4. An equation for this calculation is expressed below:

$$V_{W,Y} = \int_0^{\Phi o} x d\Phi + (365 - \Phi_o) x_o \tag{3.12}$$

where $V_{W,Y}$ is the probable annual hot water demand.

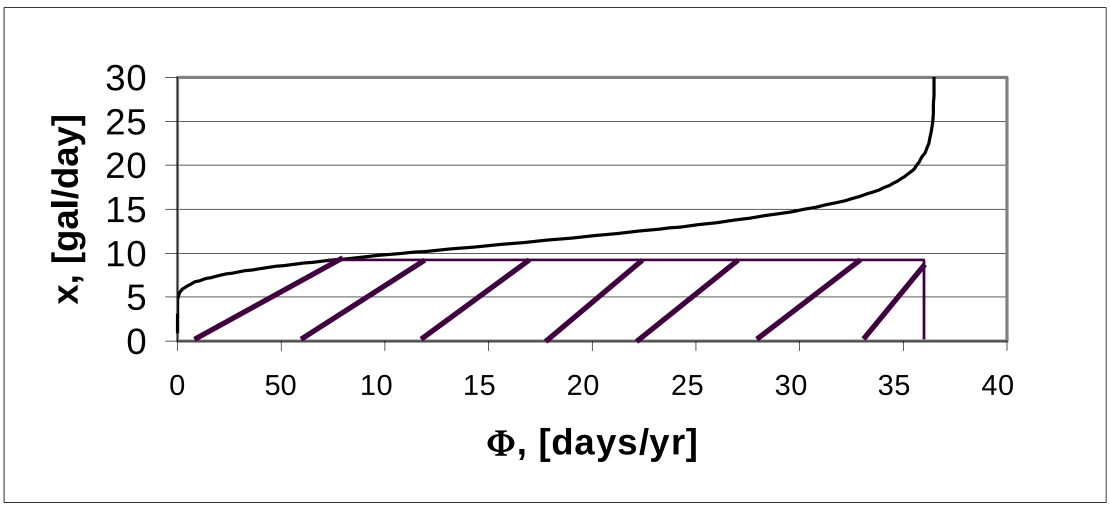

Figure 3-4: Sample Inverted Cumulative Distribution

Global Warming Analysis

Global warming is a controversial issue that many people are concerned about today. It is important to determine whether or not cogeneration technology would adversely affect global warming. It is not desirable to introduce new technology tha would increase carbon dioxide emissions.

Basic chemistry dictates that when a hydrocarbon is combusted with air, the products are water and carbon dioxide[12]. Stoichiometric analyses reveal at what molar ratios the carbon dioxide is produced. From these analyses, it can be calculated how much carbon dioxide a particular fuel emits when burned. The fuel in question is natural gas, which is dominantly methane, CH_4. Burned with oxygen, i.e., assuming nitrogen does not partake in the chemical reaction, the following chemical balance describes the combustion of methane:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \tag{3.13}$$

Data obtained from the Energy Information Administration of the Department of Energy reveals that in 1996, 2.27% of the electric power generated in the United States was fueled by petroleum, 55.74% by coal, and 8.71% by natural gas[5]. These are the only types of electric power generation that emit any significant amount of carbon. Nuclear power plants do not emit any carbon, and hydroelectric emissions are negligible. In 1996, 32.13 quadrillion Btus of electric power were generated. The Department also report how much carbon each of those three fuels emit. Petroleum emits 46.6 lb C/MBtu, coal emits 57 lb C/MBtu and natural gas only 32 lb C/MBtu. In 1996, of the 32.13 quadrillion Btus used for electric power generation, 11.05 quadrillion Btus became electricity. These numbers were used to calculate a factor that shows how much carbon is emitted by the average U.S. power plant on the basis of electricity generated for use.

Petroleum: 2.27% (32.13E15 Btu) (46.6 lb C/MBtu) = 0.03399E12 lb C

Coal: 55.74% (32.13E15 Btu) (57 lb C/MBtu) = 1.021E12 lb C

Natural Gas: 8.71% (32.13E15 Btu) (32 lb C/MBtu) = 0.08955E12 lb C

Summing the above three numbers together, the total carbon emissions in 1996 was 1.144E12 lb. Now a carbon emissions factor can be found, per kW-hr of electricity generated:

$$\frac{1.144E12 \text{ lb C}}{11.05E15 \text{ Btu of electricity generated}} = 0.353 \text{ lb C/kW-hr of electricity generated}$$

Although a cogenerator burns more natural gas than a water heater, producing more carbon in order to heat water, it simultaneously produces electricity, thereby decreasing much more dramatically the amount of emissions produced by the power plant. The total carbon emissions reduction (CER) due to using a cogenerator, is given by:

$$CER = 0.353\left[\frac{lbC}{kW-hr}\right]E_{COG} - 32\left[\frac{lbC}{MBtu}\right]\eta_E Q_{GAS,COG} \tag{3.14}$$

where the term $\eta_E\ Q_{GAS,COG}$, as shown in equation (2.16b), is the increase in gas burned by the cogenerator over the water heater. Again, all of the terms on the right hand side are expressed on a daily basis, so CER is the carbon emissions reduction on a daily, or any desired time period, basis as well. Substituting equation (2.11) into equation (3.14) gives:

$$CER = 0.353\left[\frac{lbC}{kW-hr}\right]E_{COG} - 32\left[\frac{lbC}{MBtu}\right]\eta_E \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_R (1-\eta_E)} \tag{3.15}$$

CHAPTER IV

MICRO-COGENERATION SYSTEM COMPONENTS

Micro-Turbine Generators

Small gas turbine generators are relatively new to the market. Other companies besides Capstone are developing them, such as the Northern Research and Engineering Corporati [11], but Capstone was chosen because this company already has small turbine generators in production and available for use.

According to the relationship between the power rating of the cogenerator and the amount of hot water it can produce, seen in equation (2.15), one turbine, with a power rating of 28 kW, a load factor of 1.0, an gas-to-electric conversion efficiency 0.26 (see Table 4-1)[3] and a heat recovery efficiency 0.70, can heat 13,700 gallons per day by 40 °F. The cost of a 28-kW micro-turbine generator[3] is $36,000.

Exhaust Heat Recovery Heat Exchangers

The heat exchangers that are compatible with the 28-kW micro-turbine generators are relatively inexpensive. They can be custom-built according to the specifications of the equipment they are to be connected with. The main driver of their price is the size the heat exchanger needs to be. The temperature of the micro-turbine's exhaust is relativel high, which reduces the required size of the heat exchanger. The quoted cost of a hea exchanger[14] that is compatible with the 28-kW micro-turbine generator is about $400.

Table 4-1: Capstone Micro-Turbine Driven Generator Specifications

Output	**Power**	**Efficiency (LHV)**	**Heat Rate (LHV)**
Microturbine @ 50 or 60 Hz*	28kW net	26% (+/- 0.5%points)	13,200 Btu/kWh
Emissions** (natural gas fuel): NOx		<9 ppmV / 6.7g/hr / 0.0147 lb/hr	
Noise Level		65 dba @ 10 meters	
Full Load Fuel flow (natural gas-HHV)		410,000 Btu/hr / 428,000 kJ/hr	
Exhaust Gas Temperature		520ºF / 271ºC	
Total Exhaust Energy (base @ 59ºF. 15ºC)		277,000 Btu/hr / 295,000kJ/hr	
Dimensions		74.8"H x 28.1"W x 52.9"D 1900mm H x 714mmW x 1344mmD	
Weight		1,052lbs / 478 kg	
Voltage		400-480 VAC 3 phase, 4-wire wye or 3-wire wye, ungrounded delta, 43A max	
*ISO conditions, 59º F (15º C) /sea level; for high pressure natural gas **At full-load power			

CHAPTER V

ATHLETIC CLUB OPERATIONS DAT

Description and Monthly Utility Usage History

The facility chosen for this study was the Athletic Club Northeast (ACN). This club has two washing machines, three dryers, and two water heaters. The sizes and thermal energy inputs of the washers, dryers and water heaters are reported in Table 5-1. Approximately 80 towels are washed in each washer cycle. One dryer cycle dries about 60 towels. Their space is heated by natural gas and cooled by electric air-conditioning.

Table 5-1: Health Club Appliances

Appliance	Size	Quantity	Thermal Input
Washing Machine	30”D X 22”L	2	N/A - hot water
Dryer	36”D X 36”L	3	180,000 Btu/hr
Water Heater	500 ga	2	1,000,000 Btu/hr

The data will show that approximately 900 members use the facility and about 20,000 gallons of water are consumed there each day. In order to heat 20,000 gallons o water, each water heater must run for approximately 6.7 hours per day. The water heaters are capable of producing 50.2 gallons of hot water per minute (see Appendix A).

This health club is a relatively large facility. It has a gymnasium, with a running track, an indoor pool, an outdoor pool, an aerobics room, a cardio-vascular exercise room, a weight training room, two locker rooms with showers, spas and whirlpools, as well as a children's day care center. ACN's annual utility budget is of the order o $220,000. Their electrical budget was approximately $150,000 in a period of one year [7]. Approximately $50,000 was spent on natural gas[2] in a year, and $20,000 on water and sewage[4]. Notice that roughly 23% of their utility budget was spent on natural gas[2], which is used both for water and space heating. In addition to their large thermal demand, ACN's electricity usage[7] comprised about 68% of their utility budget in the past year.

Figures 5-1 show the club's monthly water, gas and electric usage respectively, throughout a period of a year, with their respective costs shown. Figures 5-2 show the trends of the utility usages with the concurrent ambient temperatures [10]. In these figures, the monthly usages and costs were normalized to periods of thirty days. Figure 5-2b shows that much less gas is used in the summer than in the winter. This is because a large percentage of their gas use is for building space heat, of which very little is needed during

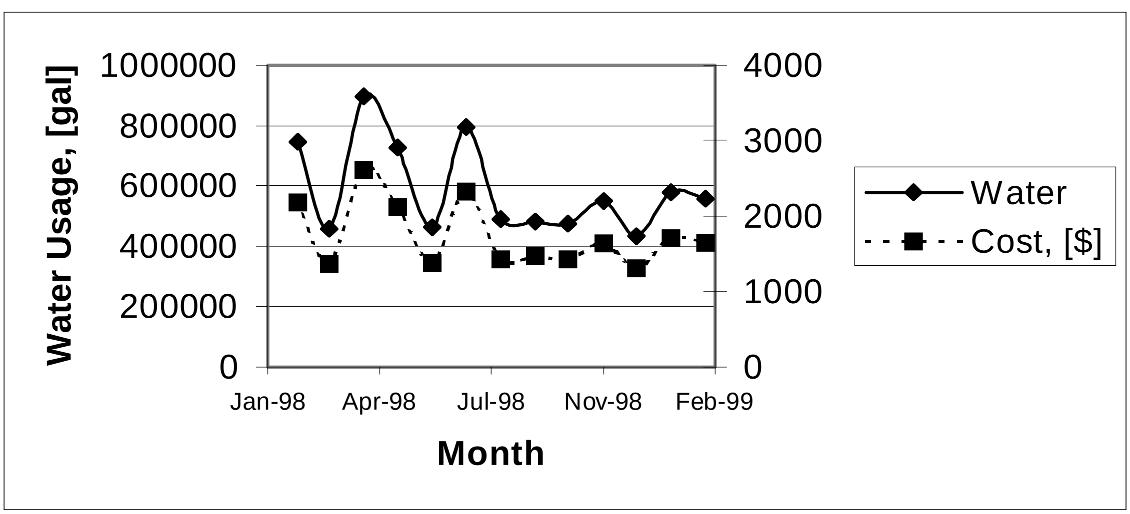

Figure 5-1a: Water Usage and Cos

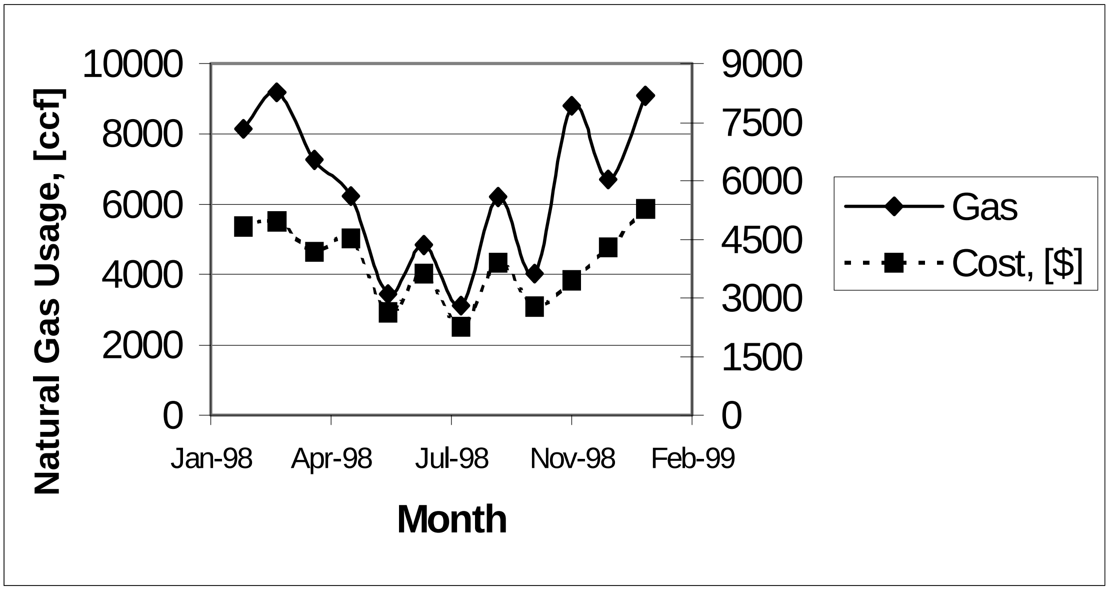

Figure 5-1b: Natural Gas Usage and Cost

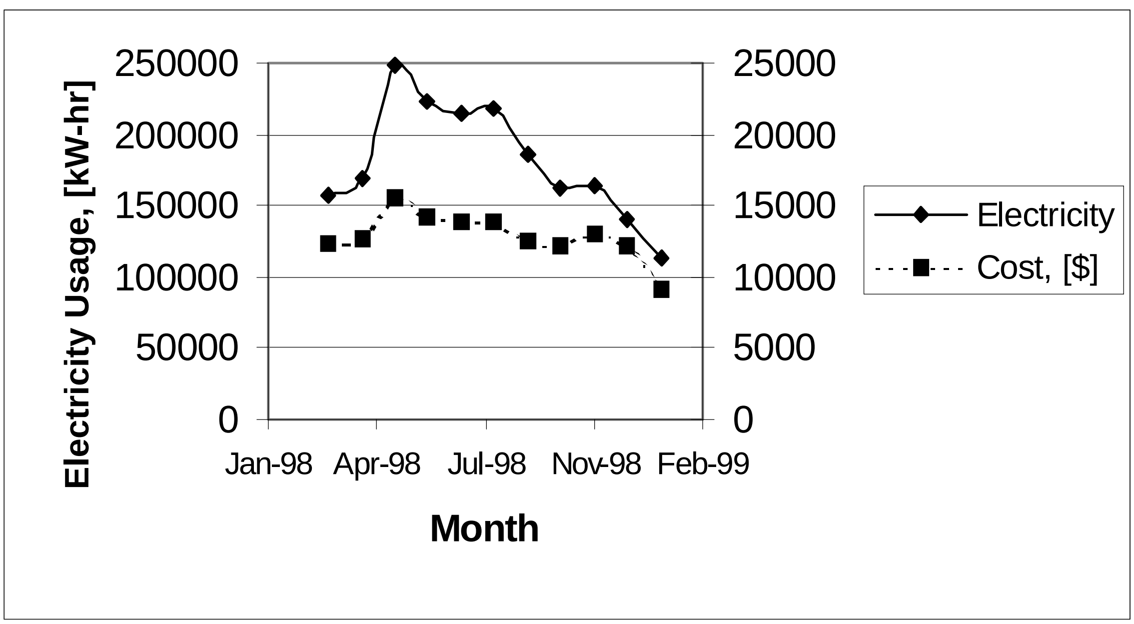

Figure 5-1c: Electricity Usage and Cos

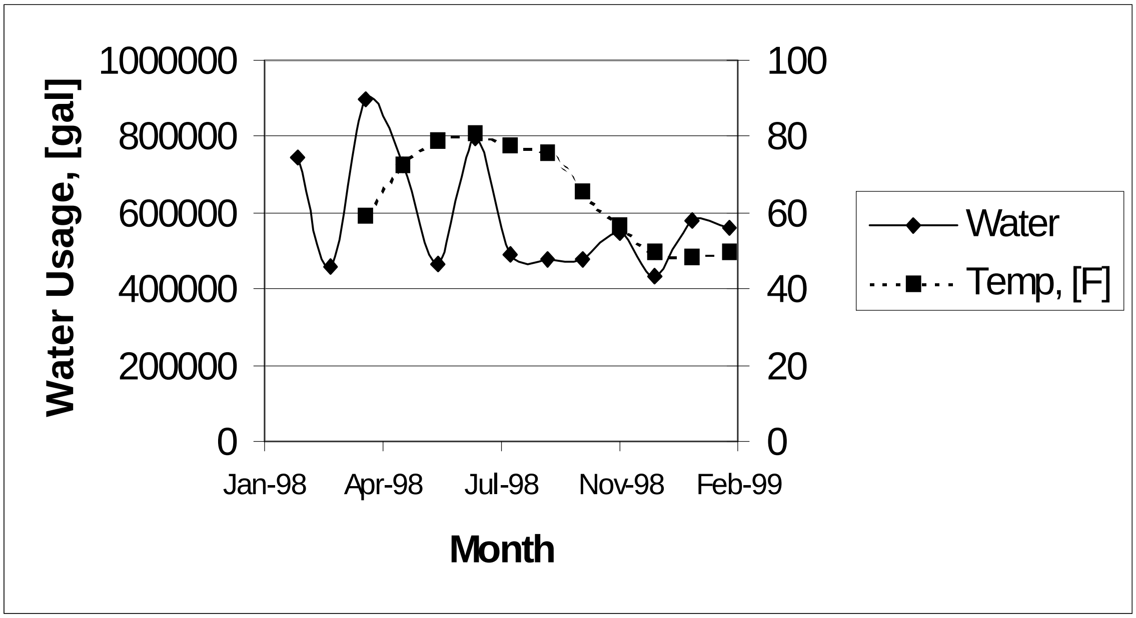

Figure 5-2a: Water Usage and Temperature

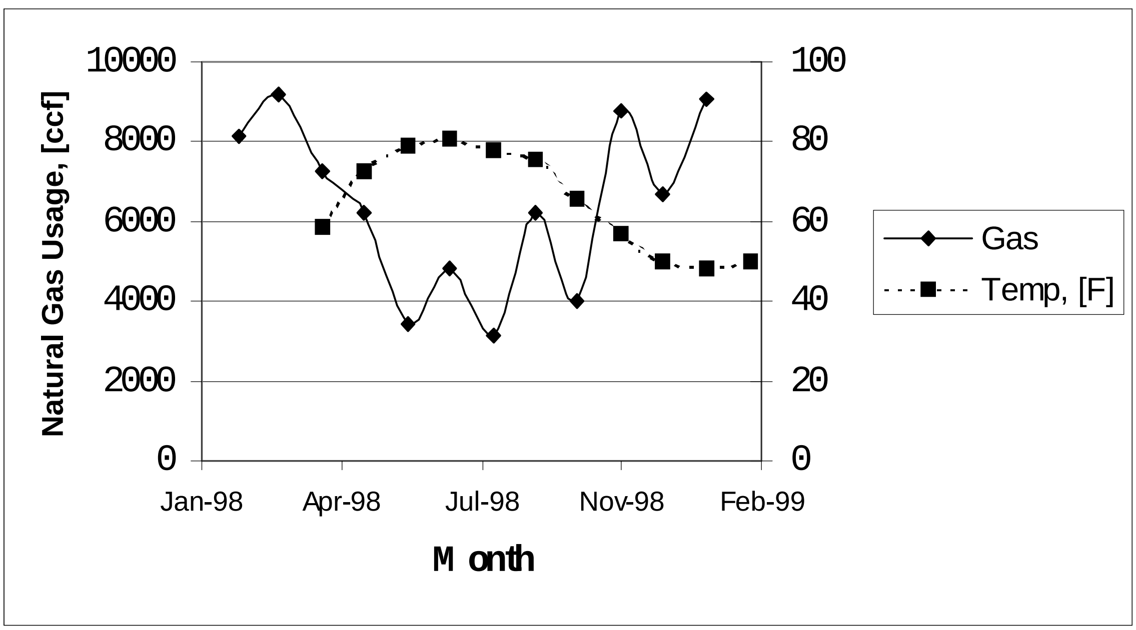

Figure 5-2b: Natural Gas Usage and Temperature

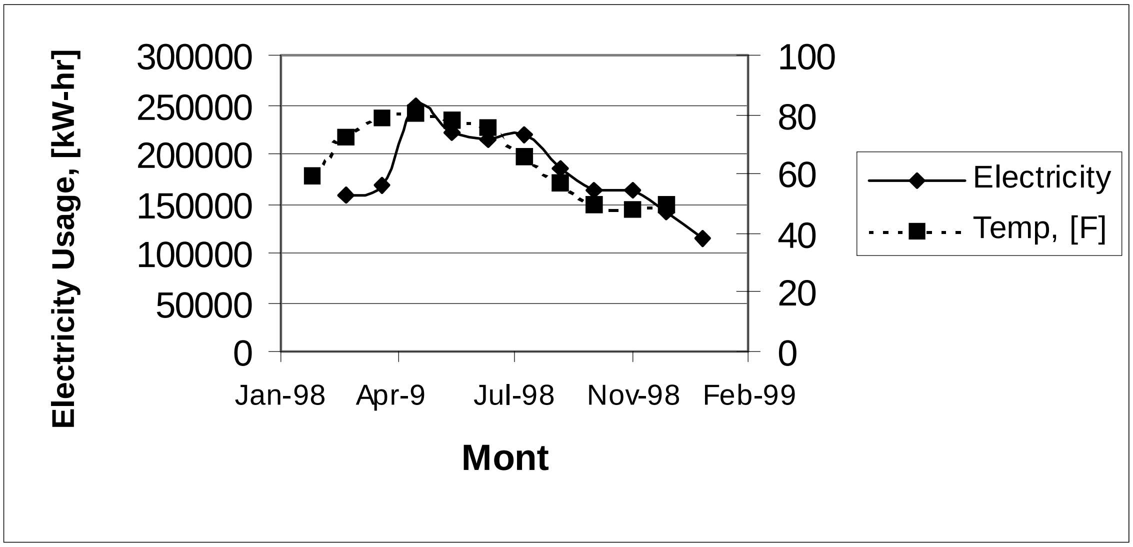

Figure 5-2c: Electricity Usage and Temperature

the hot summer months. However, some heat is still required for the spas and the outdoor pool. During those summer months, instead of heating the building, it is air-conditioned. Figure 5-2c shows a significant increase in electrical usage during the summer months. This increase is very costly to ACN. Georgia Power uses a complex rate structure to calculate the cost of ACN's electricity usage[7] (see Appendix C). The rate depends on a billing demand that is the greatest of the current month's actual peak kW demand, 95% o the peak kW demand during the summer (which they define as June through September), or 60% of the peak kW demand during the winter (October through May). For any facility that uses gas to heat their space and electricity to cool it, clearly the winter demand calculation is not going to be the largest of the three possible billing demands. The large peak demand due to air-conditioning during the summer, combined with the large amount of electricity used throughout the month, results in a high electric cost for ACN.

Using the gas usage history[2] demonstrated in Figures 5-1b and 5-2b, a distribution of gas use was estimated (see Appendix A). Summer was taken to be June through October for this calculation because ACN's gas history shows those months have a base gas load compared to May and November. Therefore, November through May were taken as the winter months. Approximating that 20,000 gallons per day of water were used, and 900 members per day use the club, and knowing the heat rates input to the washers and dryers, Figures 5-3 were created. In Figure 5-3a, the Summer Gas Distribution, it was assumed that the only space heat used was in the spas and pools. Figure 5-3b, the Winter Gas Distribution, shows that during the winter 45% of the natural gas the club used was for building space heat. Figure 5-3c shows the Overall Gas Distribution throughout an entire year. Water heating comprises 41% of ACN's natural gas needs, most of which is for the showers. (The legends in Figures 5-3 are read clockwise from the upward vertical direction.)

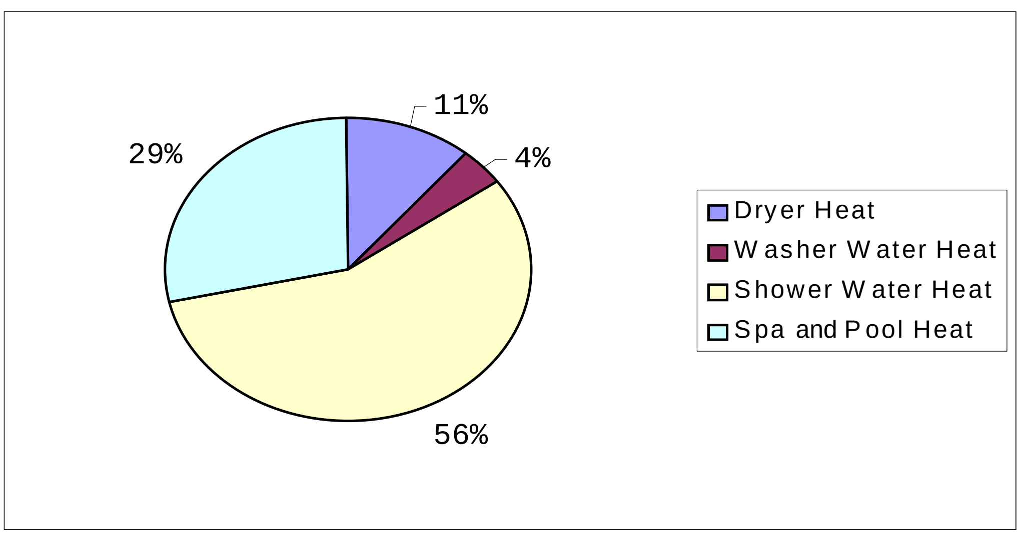

Figure 5-3a: Summer Gas Distribution

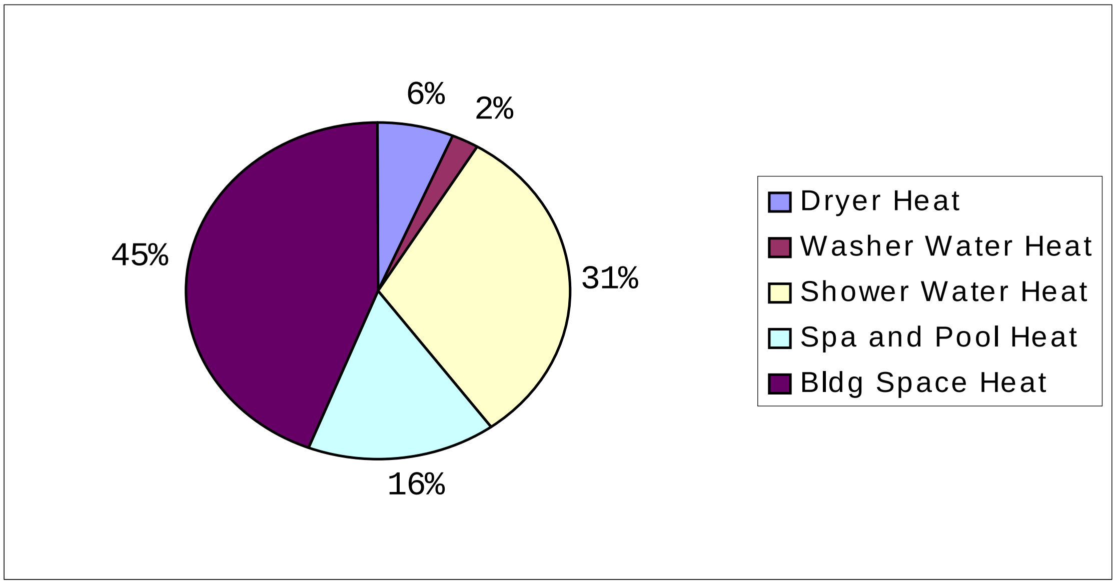

Figure 5-3b: Winter Gas Distributi

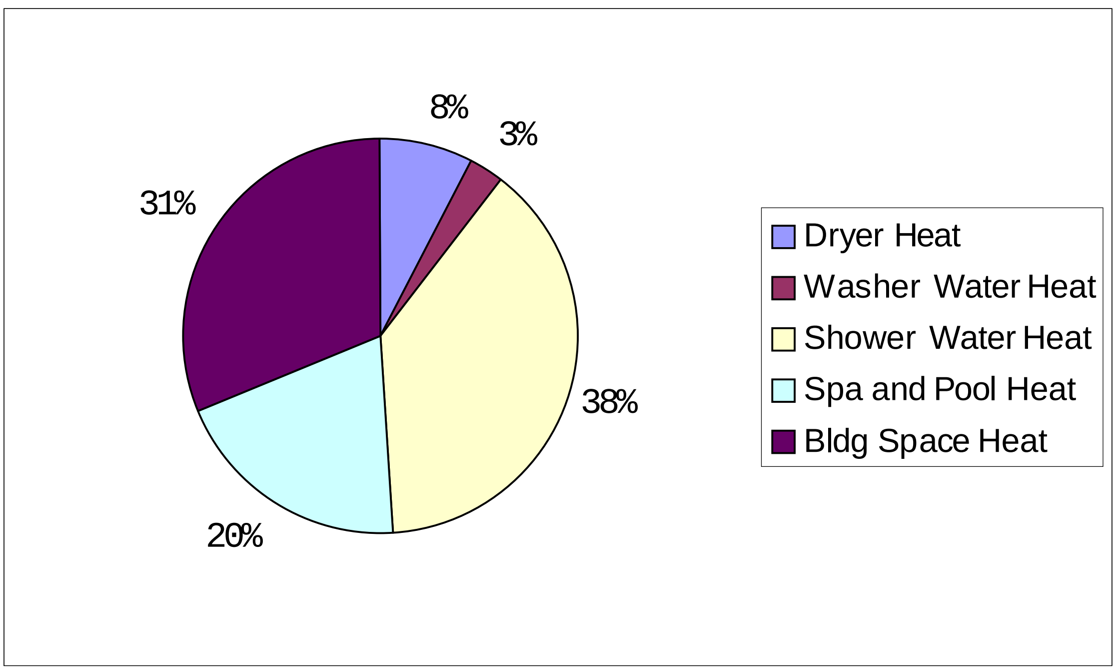

Figure 5-3c: Overall Gas Distribution

Daily and Hourly Data and Observations

In order to obtain profiles more detailed than the monthly utility usage, measurements were taken to record some daily and hourly data. Below are presented 24 points of daily gas and water usage data, 14 points of daily electrical usage data, as well as 16 points of hourly gas, water and electrical usage data. The daily data were taken on random days between February and April of 1999. The hourly data were taken on March 10. The data were correlated with the number of people using the facility at that time, with the understanding that there is a lag period between the time a member enters the club, scanning their membership card, and the time when that same member uses hot water in the showers. The club provides each member with a towel for use inside the facility. Hence, hot water is also needed to wash towels. However, the amount of ho water needed to wash the towels is almost negligible when compared with the amount o hot water used in the showers, as was shown in the Gas Distribution Figures 5-3 above. The data was also compared with the concurrent ambient temperatures. Temperature data was taken from the NOAA (National Oceanic and Atmospheric Administration) [10].

Hourly Data

Figures 5-4 represent the hourly data taken on March 10, 1999. Figure 5-4a shows the Hourly Gas Usage. The first gas reading was taken at 5:45 AM, therefore the first data point in this figure only represents 15 minutes of gas usage, from 5:45 until 6:00 AM. The fact that so little gas was used during the first 15 minutes the club was open shows that their gas usage, and therefore thermal load, is much smaller when the facility is closed. Similarly, Figure 5-4b shows that very little water was used during the first hour of operation. Some lag time occurs between the time a person starts using the facility and the time that same person showers and gets ready to leave. During the first hour, no one was using the showers. This proves that no hot water is used when the club is closed.

The dramatic decrease in gas usage at 4:00 PM (1600 hours) is partly due to some lack of resolution in the meter, which reads in ccf or 100 ft^3. That hour could also represent a time when many people are exercising and very few are showering. This idea somewhat correlates with the decrease in the Hourly Water Usage curve, Figure 5-4b, which occurs an hour earlier than the one in Figure 5-4a. Since such a small amount o water was used during the 3:00 hour, not much water needed heating during the 4:00 hour. This theory harmonizes with Figure 5-4c also. Note the large increase in people that walk through the door at 4:00 PM. They probably exercised during the 4:00 hour and those same people probably did not start using the showers until the 5:00 hour. This phenomenon is further explained in Figure 5-4d, which shows how much water each person used on an hourly basis. This curve only has dramatic changes at the beginning and end of the day. At the beginning of the day, the large change is probably due to a lag period between exercising and showering. Towards closing time, many people do not take showers at the club. They take showers at home. In the ratio of amount of water to number of persons, the numerator is decreasing, but the denominator is decreasing much faster, approaching zero because the facility is closing, resulting in the ratio increasing. Also, the one-hour lag period between the time a person exercises and the time that person showers slows down the rate at which the numerator of the ratio decreases.

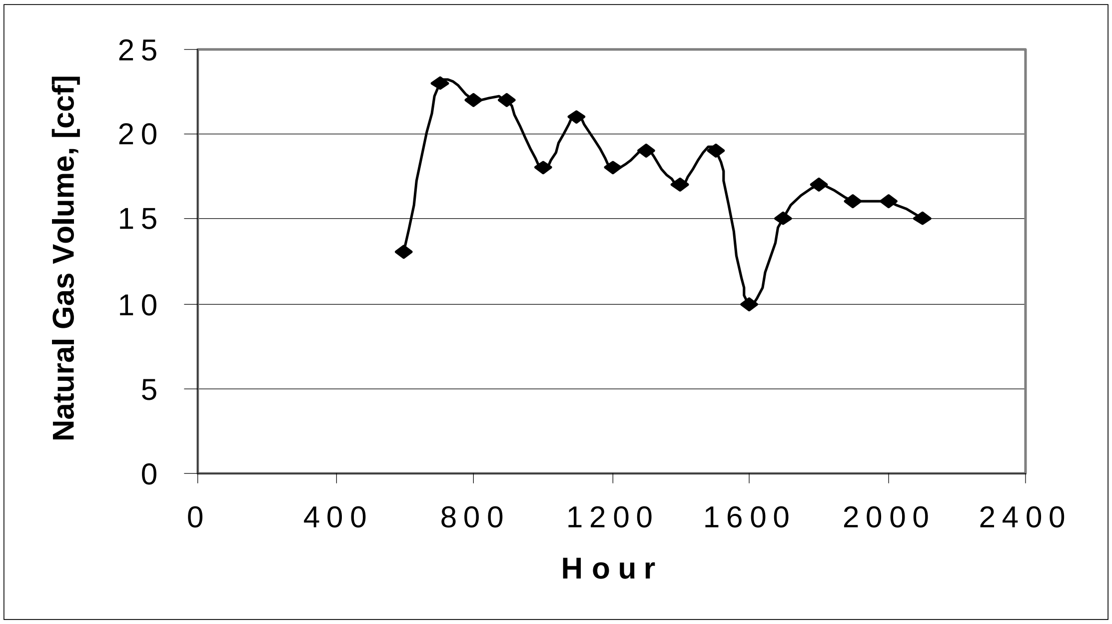

Figure 5-4a: Hourly Gas Usage

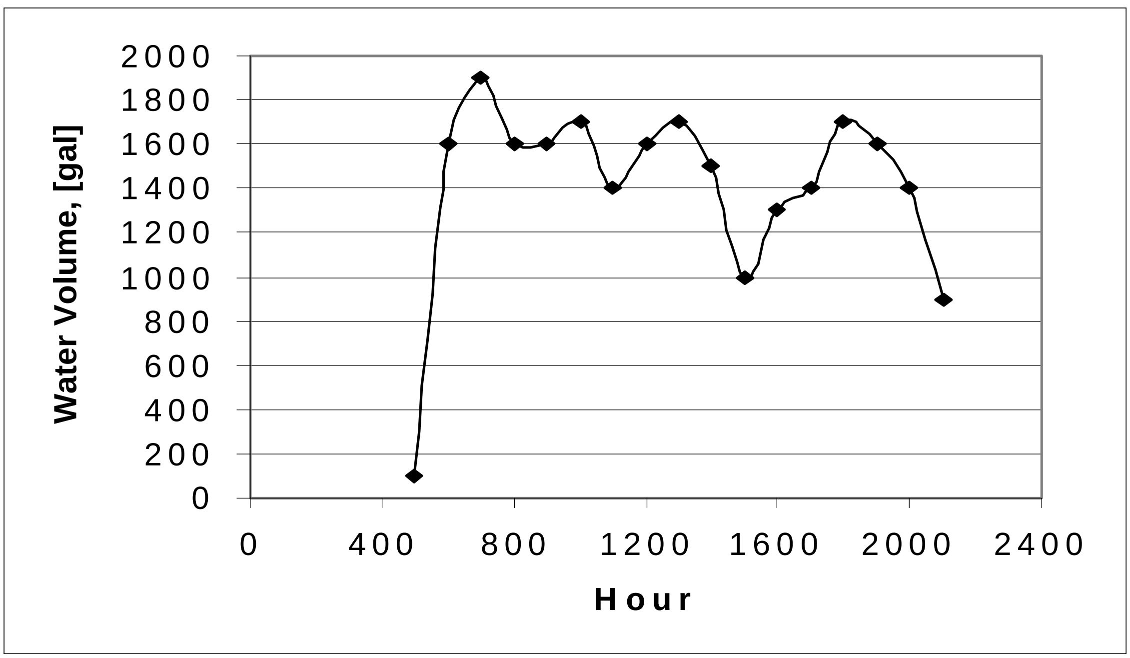

Figure 5-4b: Hourly Water Usage

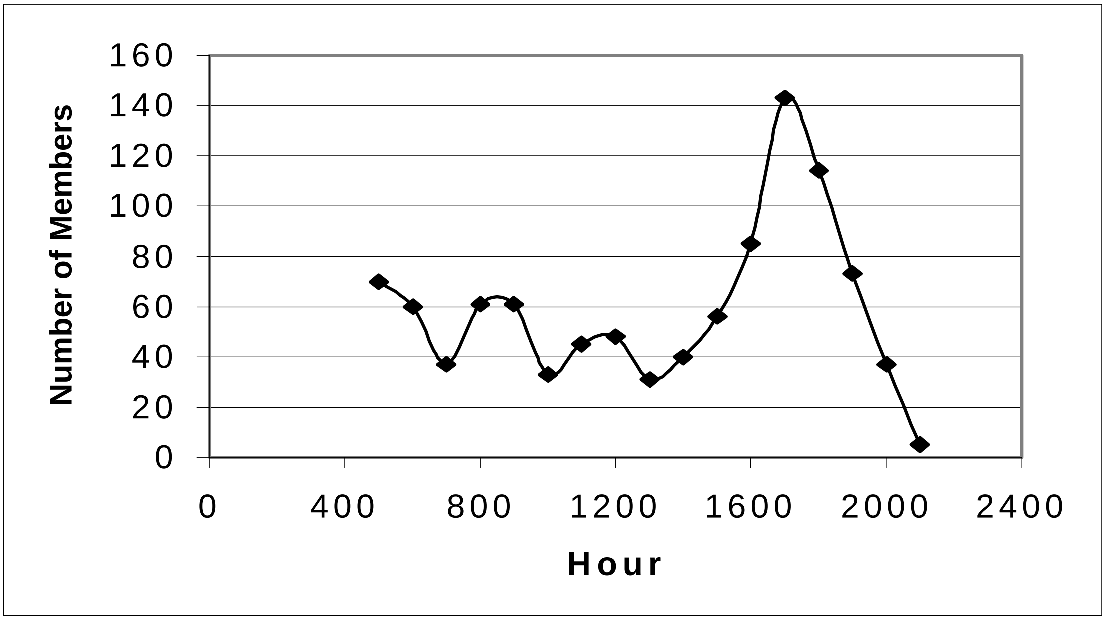

Figure 5-4c: Hourly Attendance

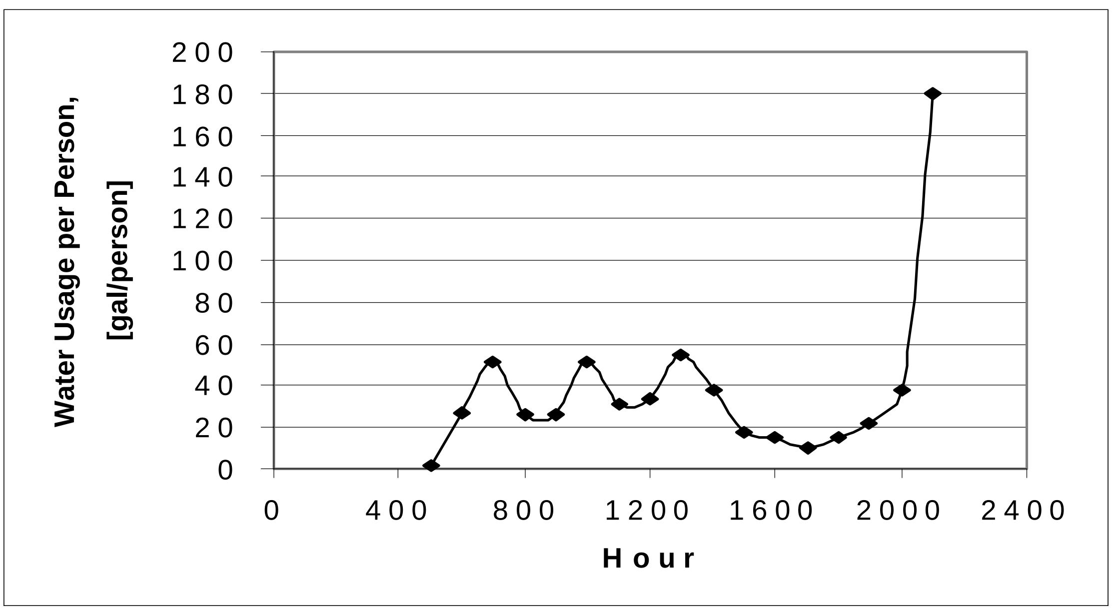

Figure 5-4d: Hourly Water Usage Per Pers

Figure 5-4e shows what the average hourly temperature was on that day [10]. It correlates with the decrease in gas usage that occurred at 4:00 PM. This may be yet another factor that explains that decrease. The peak temperatures of the day occurred during the 3:00 and 4:00 hours.

Figure 5-4f shows the Hourly Electricity Usage at the club on March 10. The large oscillations are due to the lack of resolution in the meter. It measures 500 kW-hr, i.e., the multiplier on the meter is 500. An attempt was made to estimate the meter readings to the first decimal place. This helped somewhat during the 9:00 and 10:00 AM hours.

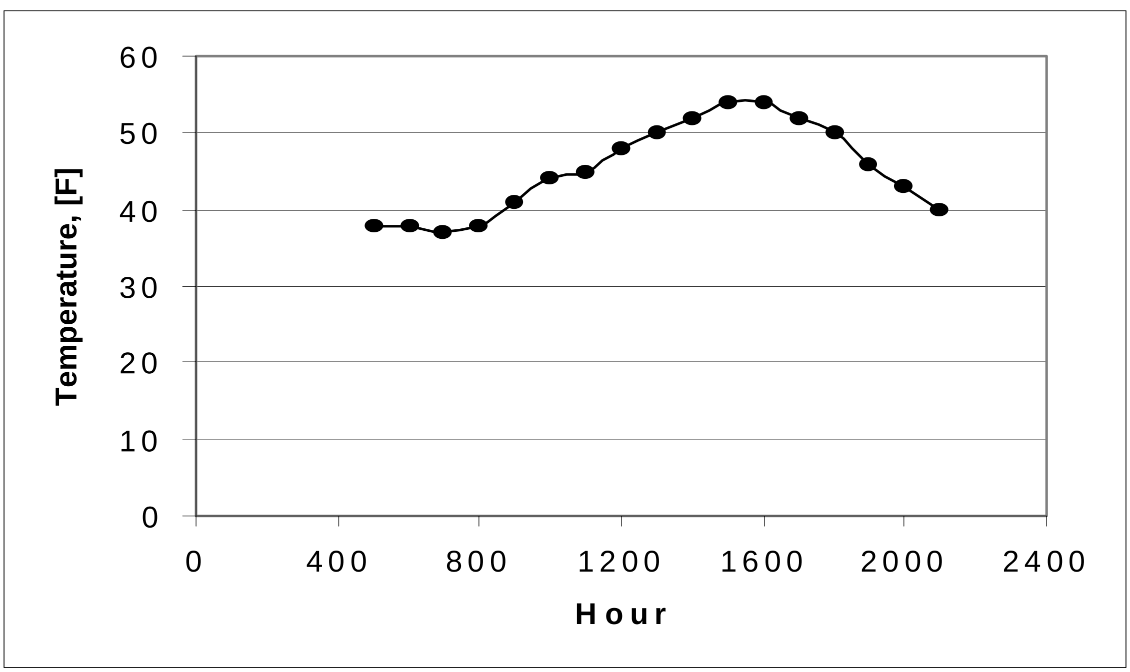

Figure 5-4e: Hourly Temperature

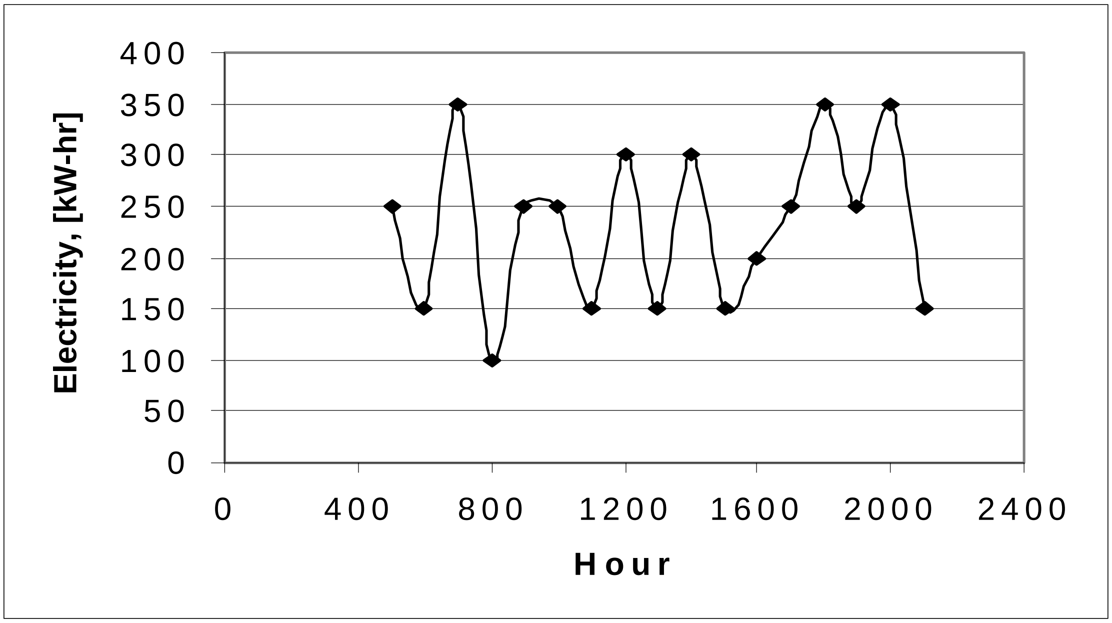

Figure 5-4f: Hourly Electricity Usage

Daily Data

The daily readings were taken at 8:00 PM. Therefore "Monday" refers to 8:00 PM Sunday through 8:00 PM Monday, etc. This time was chosen because 8:00 PM is not peak usage time, so the readings would be fairly stable and reliable. Further, the club is open every day at 8:00 PM. Their hours of operation are 8:00 AM - 8:00 PM Saturday and Sunday, and 5:45 AM - 10:00 PM Monday through Friday. The dates during which daily data was taken were February 16-24, March 4-10 and April 6-13. These correspond respectively to Day Numbers 1-9, 10-16 and 17-24. Some of the data taken in April could be interpreted as summer data because Atlanta weather was unseasonably warm [10], reaching daily averages of 74°F. The daily data are presented in Figures 5-5.

Figure 5-5a shows the Daily Gas Usage at ACN. Notice the decrease that occurs during Days 17-22. These are the April data points during which Atlanta was experiencing unseasonably warm weather. The facility required less natural gas for space heating. Figure 5-5b shows the Daily Water Usage, which varies only somewha throughout the term. Figure 5-5c shows the Daily Attendance. The lowest data points occur on Fridays, Saturdays and Sundays (Days 4-6, 11-13, and 20-22), Sundays being the lowest of all. Similarly, the highest data points in Figure 5-5d, Daily Water Usage per Person, occur on Fridays, Saturdays and Sundays. Compared to weekdays, people are more relaxed on Saturdays and Sundays and can arrive at the club early enough to make sure they have time to take a shower at the club before it closes. On Fridays, the increase probably occurs because people tend to go out on Friday nights instead of going to a health club. Therefore, the persons who would normally go to the club shortly before closing and shower at home, do not go to the club at all, decreasing the denominator of the ratio and thereby increasing the ratio of water used per person. Contrarily, during the week, people who have to work and then exercise after work are likely shower at home, decreasing the numerator and thereby decreasing the ratio. The average daily temperatures[10] are expressly shown in Figure 5-5e. Figure 5-5f, Daily Electricity Usage, shows a generally larger consumption during the warmer April days. It correlates with the decrease in gas usage seen in Figure 5-5a and the increase in temperature seen in Figure 5-5e, although again, due to lack of resolution in the meter, the data has some scatter.

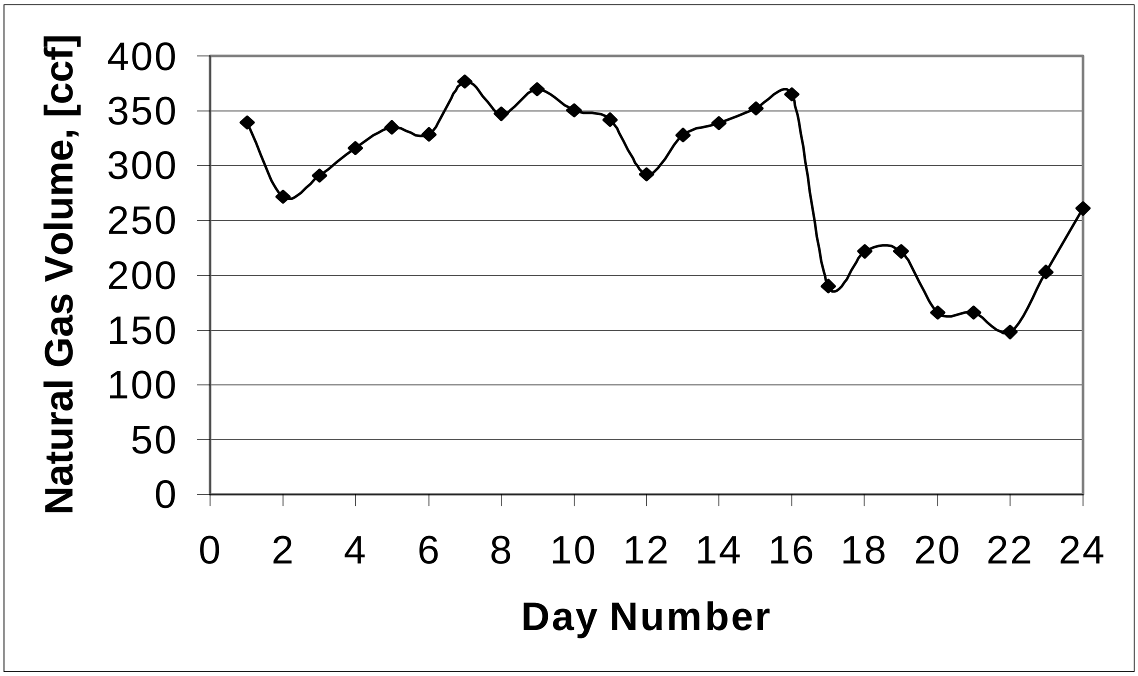

Figure 5-5a: Daily Gas Usage

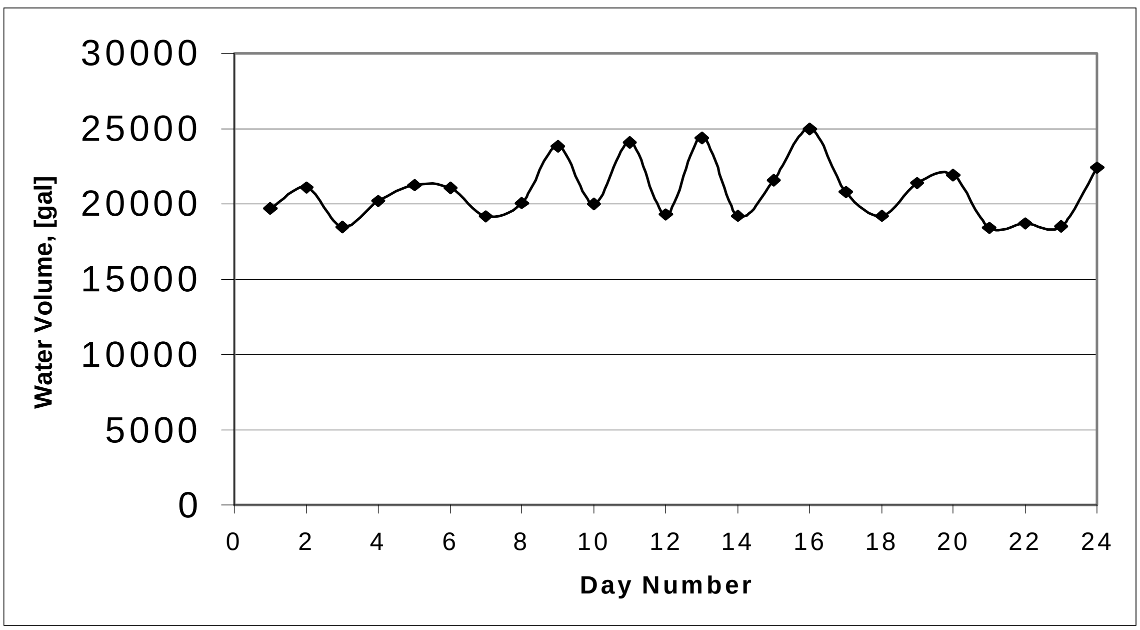

Figure 5-5b: Daily Water Usage

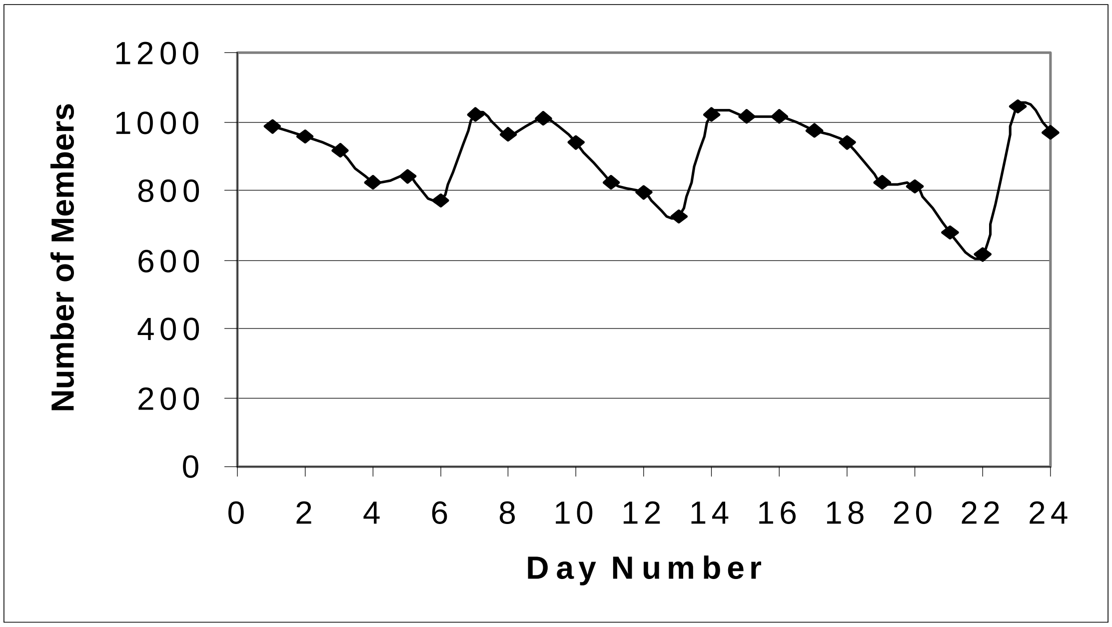

Figure 5-5c: Daily Attendance

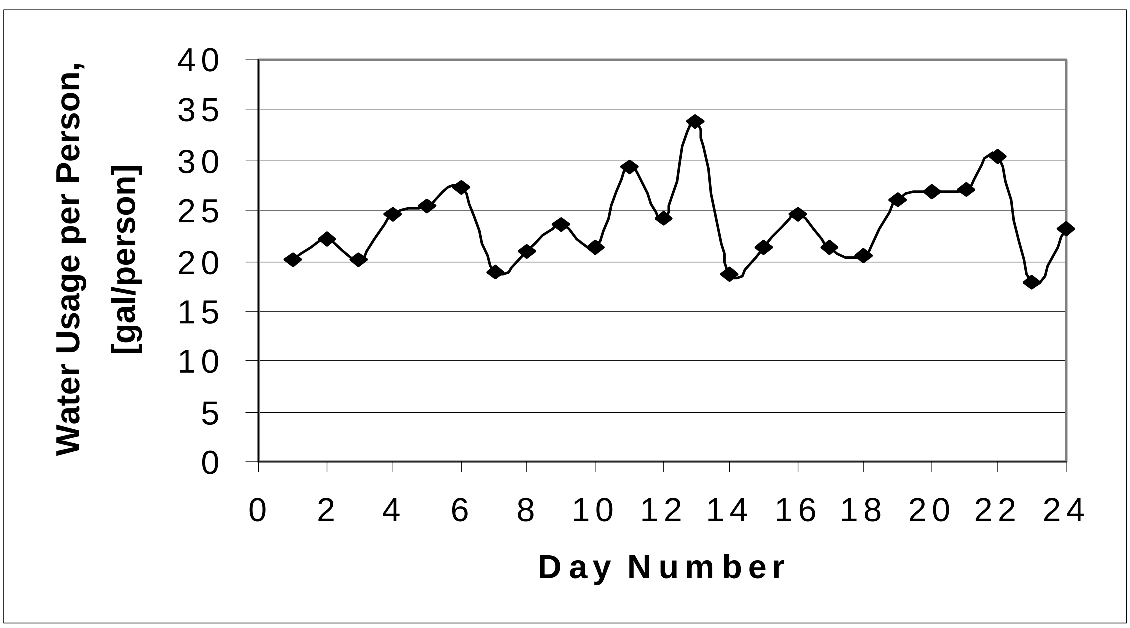

Figure 5-5d: Daily Water Usage Per Person

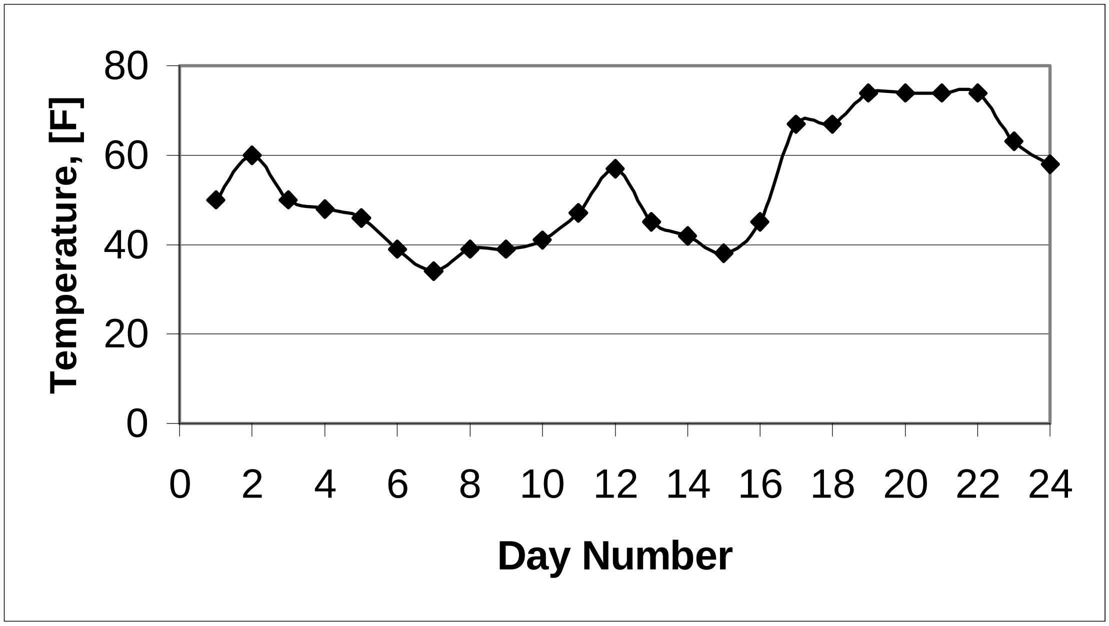

Figure 5-5e: Daily Temperature

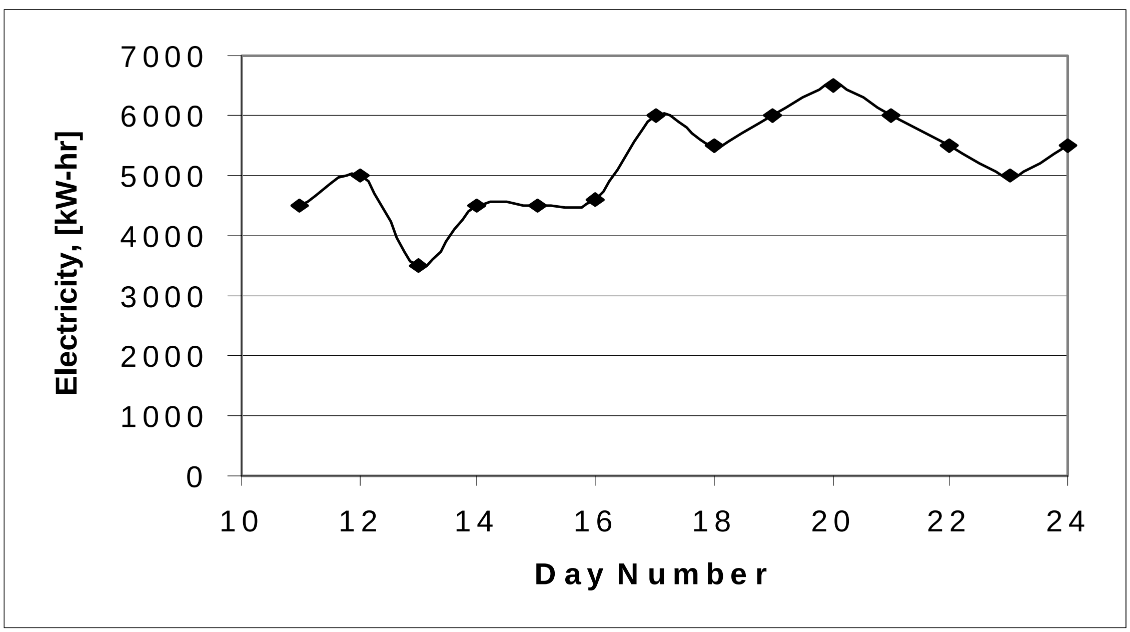

Figure 5-5f: Daily Electricity Usage

Summary of Observations

The data shows that on a typical day, the club uses approximately 20,000 gallons of water, 330 ccf of natural gas and roughly 4,500 kW-hr of electricity during colder weather. During warmer weather, the electricity consumption increases to approximately 6,000 kW-hr per day to run the air conditioning system(s). Likewise, the gas consumption decreases to approximately 200 ccf per day. This harmonizes with the corresponding temperatures during those periods, as well as their utility usage history.

CHAPTER VI

RESULTS AND DISCUSSION

Economic Impac

The net savings and the simple pay back period of the cogeneration system partly depend on how much more natural gas the system would use than the water heaters. The first law of thermodynamics and the heating value of natural gas were applied to the natural gas-fired water heater, as seen in equations (2.1) and (2.2), to calculate how much of the known gas usage of the facility was used to heat water. A water heater efficiency of 70% was used, and a natural gas heating value of 1026 Btu/ft^3. Figures 6-1 compare the total natural gas usage with the amount of gas required to heat water from the corresponding temperature that hour, or day, to 105 °F, respectively. Figure 6-2 represents the same calculation as Figure 6-1a, only with lag periods of 30 minutes and one hour.

The calculated quantity of gas necessary to heat water to 105 °F, daily, was then subtracted from the total daily gas usage and plotted with the average daily temperature[10] in Figure 6-3. The trendline in Figure 6-3 demonstrates that the amount of gas used besides that for heating water, i.e., for space and pool heating, decreases as temperature increases. The reason it does not approach zero at temperatures where no space heating is used is because even during warm weather, the spas and the outdoor pool continue to be heated. Some heat is also used for the dryer, although it is small compared with the space and water heating requirements, as was shown in Figures 5-3.

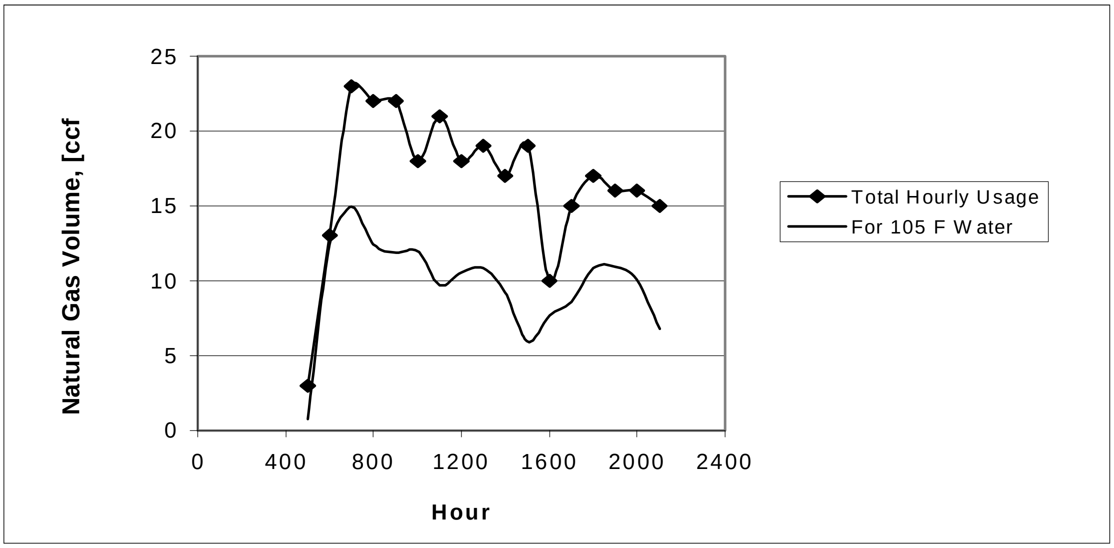

Figure 6-1a: Hourly Gas Usage Comparison

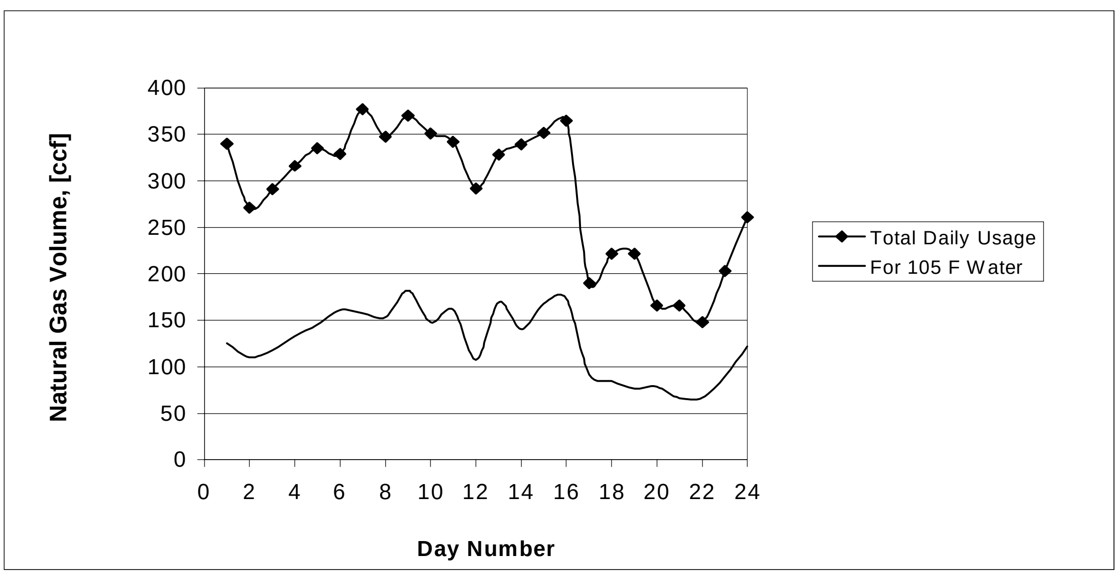

Figure 6-1b: Daily Gas Usage Comparison

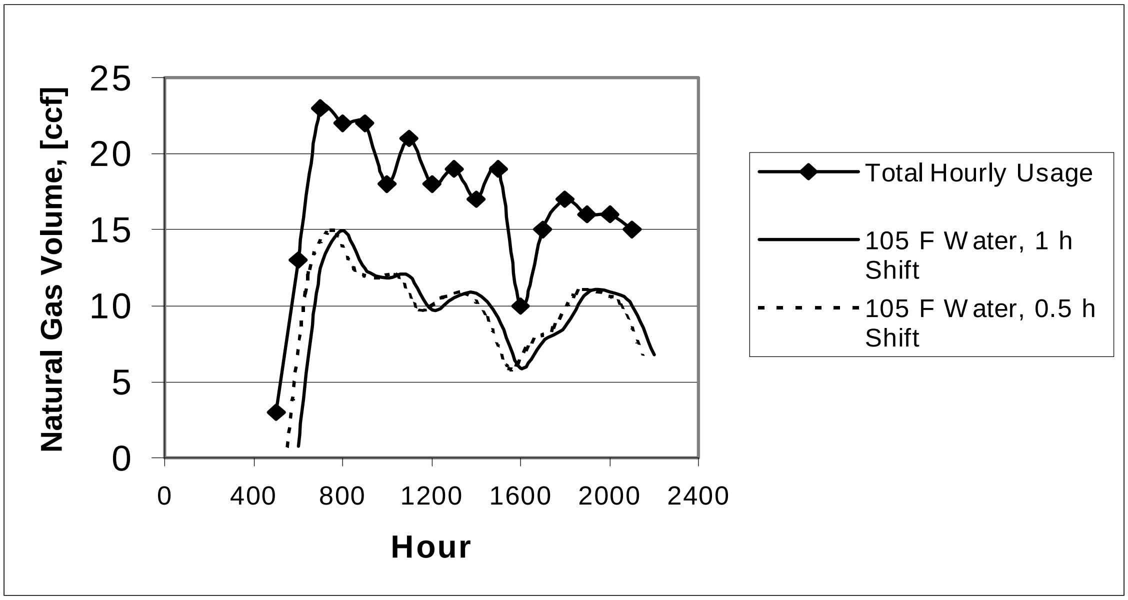

Figure 6-2: Hourly Gas Usage Comparison with Lag Time

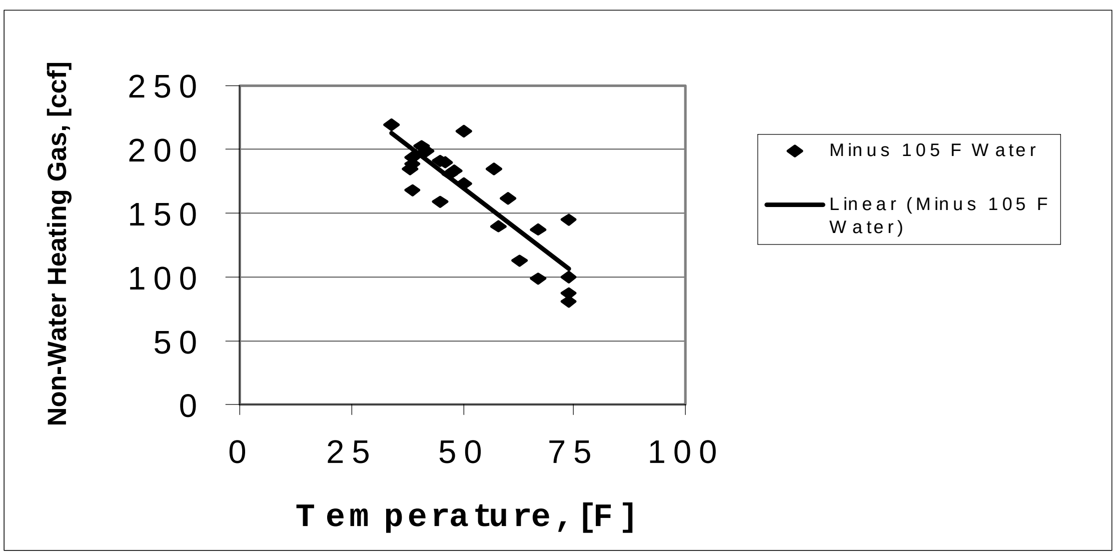

Figure 6-3: Daily Non-Water Heating Gas vs. Temperature

The economic characteristics of the cogeneration system also depend partly on the size the cogenerator needs to be, and therefore the amount of hot water it can produce.

statistical distribution of the daily water usage data was applied to the probability density function in order to demonstrate the facility's water usage pattern. This analysis was shown in equations (3.7), (3.8) and (3.9). The probability distribution [8] of the daily water usage data is shown in Figure 6-4a. A histogram of the daily water usage data provided in Figure 5-5b was compared with the fitted probability density function in Figure 6-4b. The discrepancies in this comparison can be explained by several possibilities, e.g., som scatter in the data and lack of resolution in the meter. If more daily data was available, the validity of the assumed lognormal distribution could have been better determined.

The inverted cumulative distribution[8] of the water usage is shown in Figure 6-5. This figure was created by means of equations (3.10) and (3.11). Figure 6-5 shows that in order to meet 95% (347 days out of the year) of the service hot water thermal load at Athletic Club Northeast, they need 80 kW of turbine power output. Three 28-kW micro-

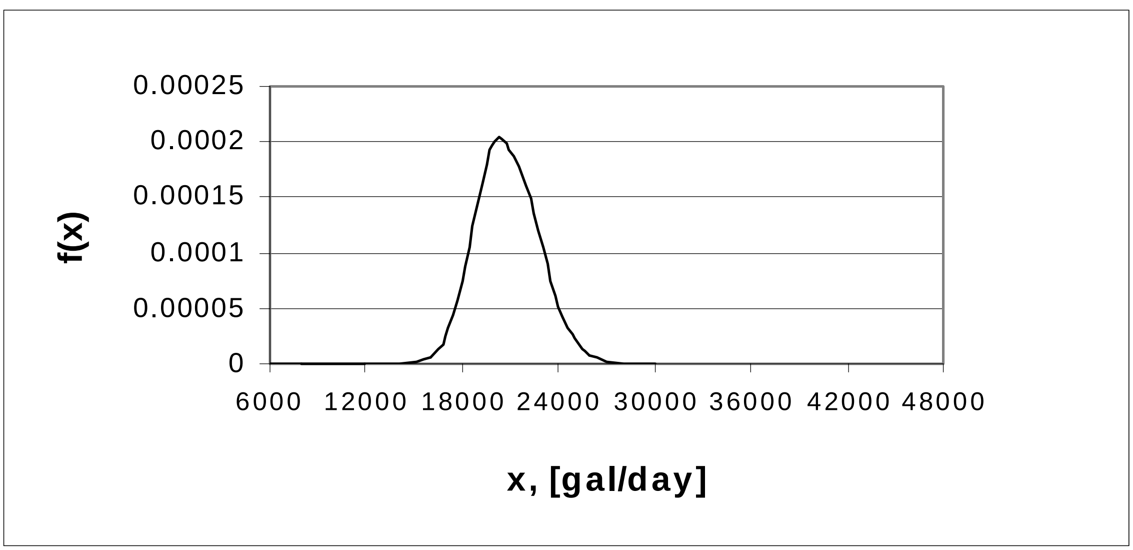

Figure 6-4a: Probability Density Functi

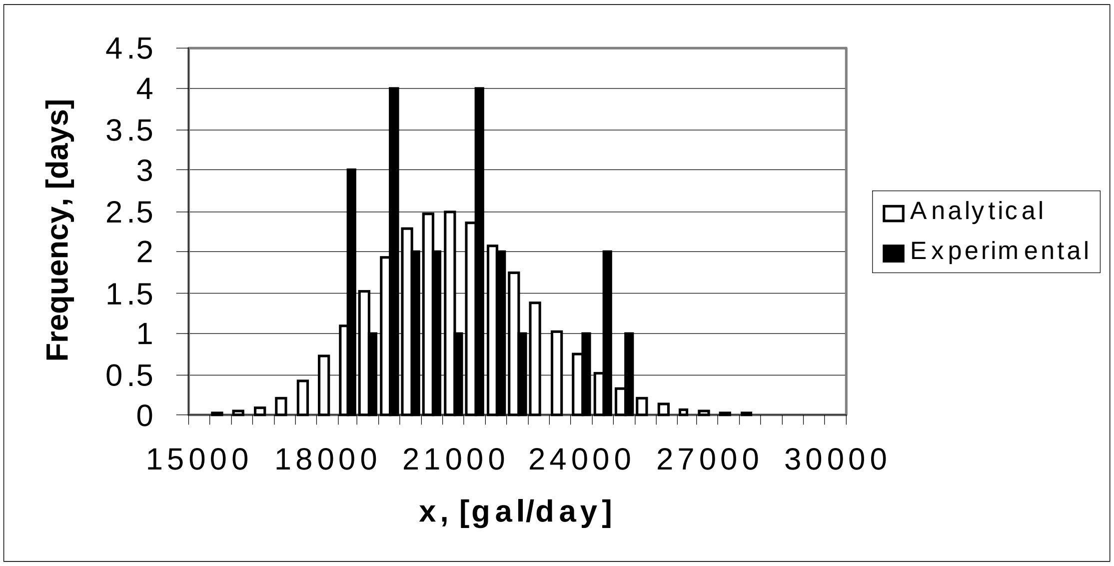

Figure 6-4b: Histogram of Daily Water Usage Data

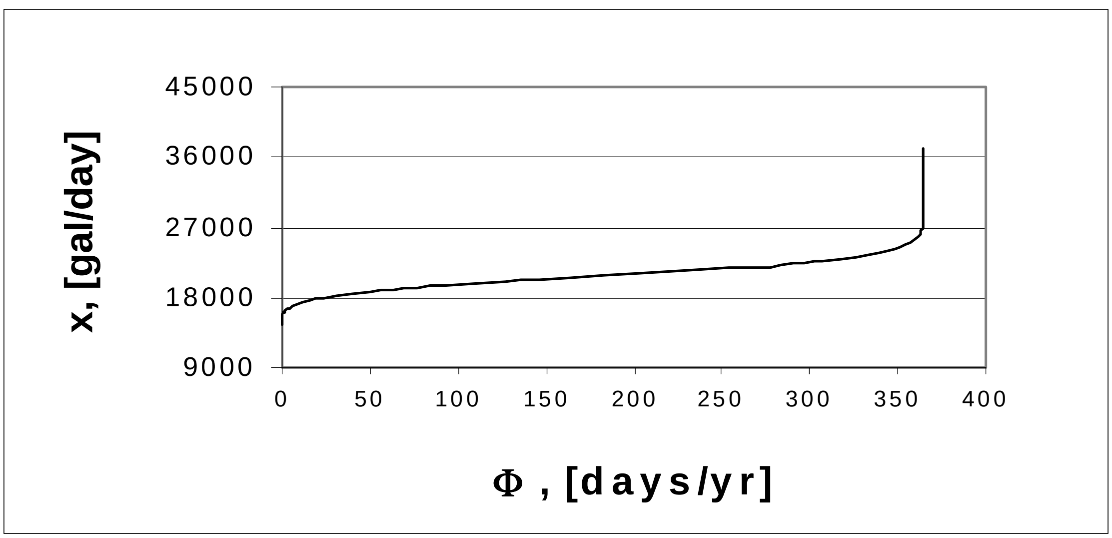

Figure 6-5: Inverted Cumulative Distribution

turbines are necessary to meet this requirement, which is actually 84 kW of power. This in turn actually means 98% of their annual hot water needs would be satisfied. The res of their thermal hot water load can be met as it is now, by the gas-fired water heater, but this would be quite rare.

As discussed earlier, the health club does not consume any hot water when it i closed. If the cogenerator were run when the club is closed, the hot water it produced would have to be stored and the facility would likely have to purchase a large tank for that purpose. Further, the cogenerator would be producing electricity at a time when electricity is not being used. This would be wasteful. It is really only practical to run the cogeneration system during business hours, because that is when the facility experiences thermal and electrical demands. Knowing the business hours of the facility, and assuming 100% of full load, the maximum hours of daily runtime of the cogenerator can be found for the situation where the cogenerator never runs while the club is closed, but only during business hours:

$$RT_{MAX} = \frac{2\left[\frac{days}{weekend}\right]12\left[\frac{hr}{day}\right] + 5\left[\frac{weekdays}{week}\right]16.25\left[\frac{hr}{weekday}\right]}{7\left[\frac{days}{week}\right]}$$

(6.1a)

$$RT_{MAX} = 15\left[\frac{hr}{day}\right]$$

(6.1b)

where RT_{MAX} is the maximum daily runtime of the cogenerator. This equals the average number of business hours in a day. The corresponding maximum load factor is equivalent to that number non-dimensionalized:

$$LF_{MAX} = 0.625 \text{ or } 62.5\%$$

(6.1c)

where LF_{MAX} is the maximum load factor.

The first law of thermodynamics relates the power rating of the cogenerator to the amount of hot water it can produce. This relationship was demonstrated in equati (2.15). Assuming the maximum load factor of 0.625, Figure 6-6 shows what size cogenerator is needed to produce a given amount of hot water.

The general economic characteristics of the cogeneration system can now be plotted with the power rating of the cogeneration system. A fixed cost of electricity was initially assumed for this calculation in order to obtain preliminary estimates of the ne savings and simple pay back period of the cogenerator. That fixed rate was taken as \$0.062/kW-hr. Knowing how much hot water a certain size cogenerator can produce, and knowing the cost of gas, equation (3.4b) was then used to create Figures 6-7, the Estimated Net Annual Savings and the Estimated Simple Pay Back Period of the cogeneration energy system. These calculations also included sales tax, which is 7% in Georgia. Note how the pay back period increases as the cogenerator equipment cost, C_{COG}, increases. The impact diversified data has on the economics of cogeneration are also demonstrated in Figures 6-7. Multiplying the standard deviation of the data, in this case by a factor of ten because σ_{LN} was very small, shows that the more scatter there is in the hot water usage profile, the lower the savings of the cogeneration system can be. This results in a longer pay back period as well. The economic characteristics can be better, but only for systems that are too large to be practical for this facility's needs, as will be discussed later.

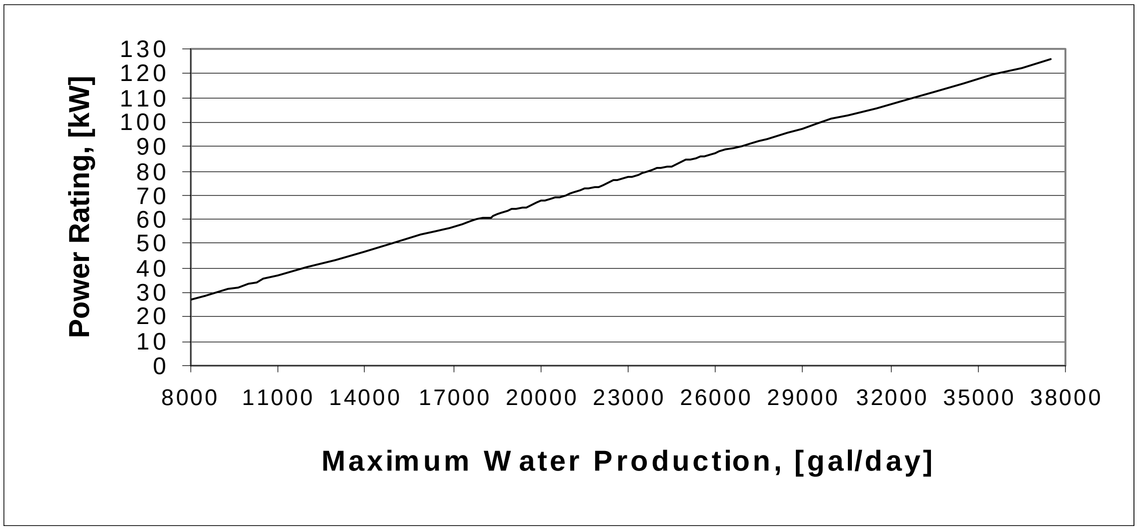

Figure 6-6: Turbine Power Rating

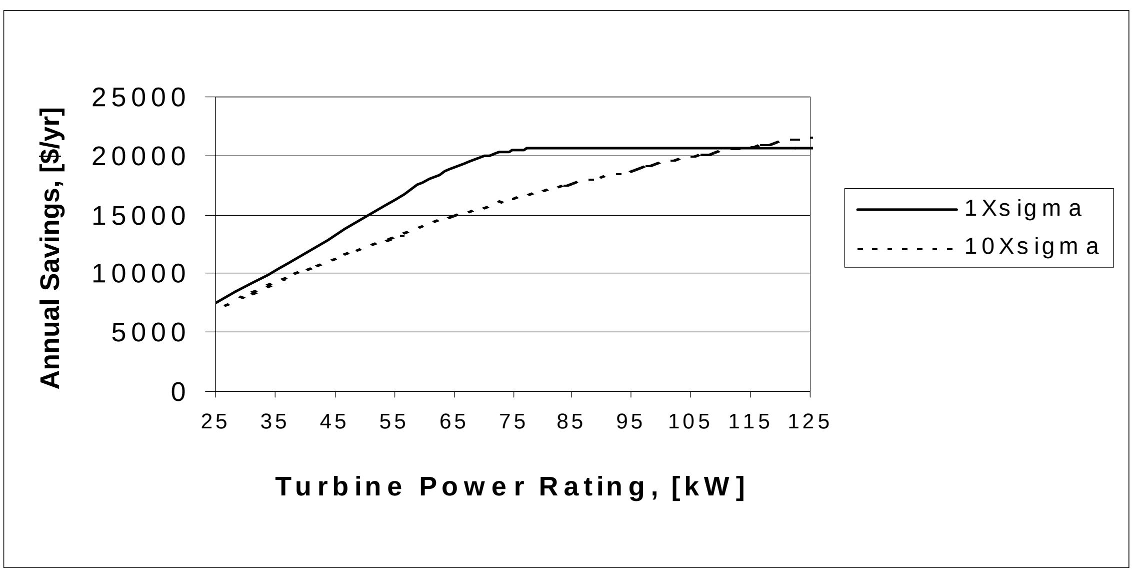

Figure 6-7a: Estimated Net Annual Savings

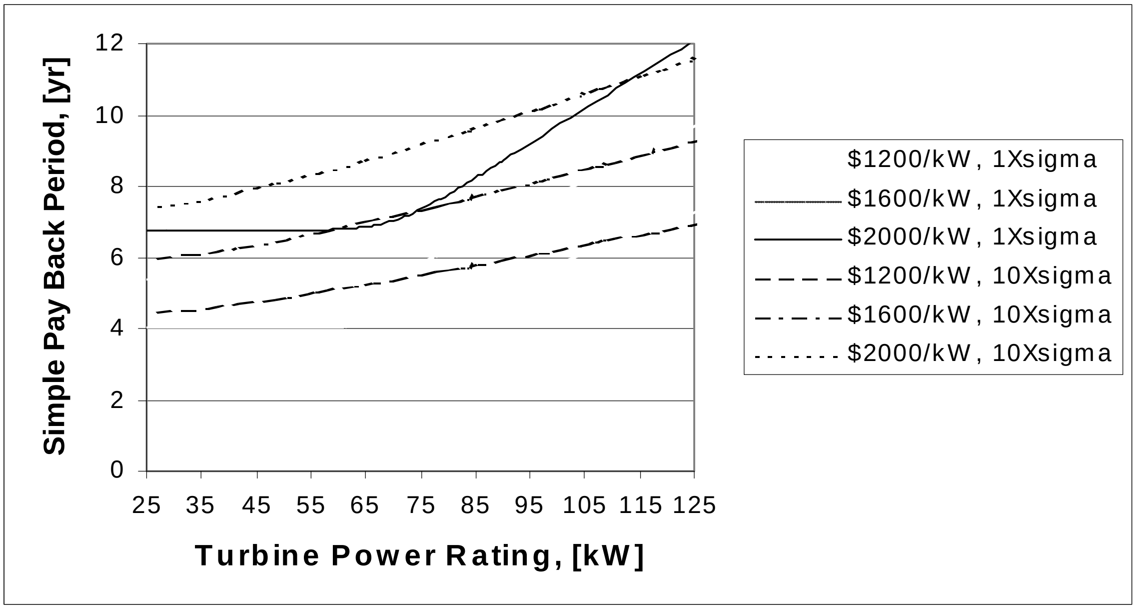

Figure 6-7b: Estimated Simple Pay Back Period

At certain times of the year the cogenerator is oversized to meet its probable daily requirement. The maximum amount of hot water that the cogeneration system could produce in a year, $V_{W,Y}$, was found by using equation (3.12). Dividing this number by the maximum daily hot water production of the cogenerator, which is equal to x, gives the number of hours the cogenerator would actually be run throughout a year:

$$t_y = \frac{V_{W,Y} LF_{MAX}}{x} \tag{6.2}$$

where t_y is the annual runtime of the cogenerator. The calculation of t_y is always less than or equal to 62.5% of the number of hours in a year, 5475. This is how many business hours there are in a year. Knowing the power rating of the cogenerator and the number of hours per year that it runs, the amount of electrical energy the cogenerator would actually produce in a year, $E_{COG,Y}$, is found as follows:

$$E_{COG,Y} = t_y \dot{E}_{COG,PK} \tag{6.3}$$

Georgia Power's electrical billing structure[7] was used wit ACN's electrical usage history to determine what the exact savings and simple pay back period of implementing a cogeneration energy system would be i ACN's electrical usage continued as it did in the past year (see Appendix C). Therefore, to find the value of the electrical energ produced, again on an annual basis, multiply equation (6.3) by the exact cost o electricity noted in the electric bill histor [7]:

$$\$_{E,COG,Y} = E_{COG,Y} C_{E,DAT} \tag{6.4a}$$

where $C_{E,DAT}$ is the cost of electricity based on electric bill data. Substituting equation (6.3) into equation (6.4a) yields:

$$\$_{E,COG,Y} = t_y \dot{E}_{COG,PK} C_{E,DAT} \tag{6.4b}$$

Since ACN is billed for electricity on a monthly basis, it is necessary to calculate how many hours per month the cogenerator would run. Since the cogenerator runs to satisf the hot water thermal load, and this load is fairly constant, it is reasonable to assume tha the cogenerator runs the same amount of time every month:

$$t_m = \frac{t_y}{12}$$

where t_m is the number of hours the cogenerator would run every month. Equation (6.4b) is then adjusted for monthly terminology:

$$\$_{E,COG,M} = t_m \dot{E}_{COG,PK} C_{E,DAT}$$

(6.4c)

where $\$_{E,COG,M}$ is the value of the electricity the cogenerator would produce every month. Twelve of these are summed together to find the value of the electricity the cogenerator would produce over a year:

$$\$_{E,COG,Y} = \sum_{1}^{12} \$_{E,COG,M}$$

(6.4d)

It is necessary to use a full year of electric bill data because the amount of electricity used for space cooling at the athletic club is very different during winter months than it is during summer months, as demonstrated in Figure 5-2c.

In order to find the total annual savings of running the cogenerator, the added cost of gas to run it must be accounted for, as stated earlier in equation (3.1). Since this calculation is now based on electric bill data [7], the new notation, $\$_{SAV,DAT}$, is used to describe the savings:

$$\$_{SAV,DAT} = \$_{E,COG,Y} - \$_{GAS,COG,Y} + \$_{GAS,WH,Y}$$

(6.5)

Modifying equations (3.3b) and (3.3c) to use the annual hot water production of the cogenerator, $V_{W,Y}$, instead of the daily production, V_W, results in the following equations:

$$\$_{GAS,COG,Y} = C_G \frac{\rho_W V_{W,Y} C_{P,W} \Delta T_W}{\eta_R (1-\eta_E)}$$

(6.6)

$$\$_{GAS,WH,Y} = C_G \frac{\rho_W V_{W,Y} C_{P,W} \Delta T_W}{\eta_R}$$

(6.7)

where the subscript "Y" merely denotes that these values are annualized. Here again, the current cost of gas, C_G, is \$3.40/MBtu. The change in temperature is still based on the assumption that the average temperature of the water consumed, T_T, is 105 °F. The average ambient temperature in Atlanta over the past year[10], 63.8 °F, was used for T_C. Subtracting equation (6.7) from (6.6) gives:

$$\Delta\$_{GAS,Y} = C_G \rho_W V_{W,Y} C_{P,W} \Delta T_W \left(\frac{1}{\eta_R (1-\eta_E)} - \frac{1}{\eta_R} \right)$$

(6.8a)

where $\Delta\$_{GAS,Y}$ is the increase in the amount of money that is spent on gas throughout a year due to replacing the water heater with the cogenerator. The term in parentheses can be simplified to obtain:

$$\Delta\$_{GAS,Y} = C_G \rho_W V_{W,Y} C_{P,W} \Delta T_W \left(\frac{\eta_E}{\eta_R (1-\eta_E)} \right)$$

(6.8b)

Having derived equations (6.4d) and (6.8b), equation (6.5) can be re-written:

$$\$_{SAV,DAT} = \$_{E,COG,Y} - \Delta\$_{GAS,Y}$$

(6.9)

where all three terms are in units of \$/yr. The simple pay back period[15] is then found in the same manner as described in equation (3.6), only now with nomenclature expressing that the terms are based on the electric bill data:

$$SPBP_{DAT} = \frac{C_{COG}\dot{E}_{COG,PK}}{\$_{SAV,DAT}}$$

(6.10)

Because the equations derived in this section are based on the exact cost of electricity according to ACN's billing history, they were used to create Figures 6-8. Figure 6-8a demonstrated the Net Annual Savings and Figure 6-8b, the corresponding Simple Pay Back Period. Here again, a sales tax of 7% was accounted for. These figures reemphasize the effect a more diverse water usage profile has on the economic characteristics of the cogeneration energy system by showing curves in which the standard deviation was multiplied by ten.

The 28-kW Capstone stand-alone low-pressure micro-turbine generators cos \$36,000. A reasonable maintenance cost for such a system would be around 3% of its purchase cost per year[1]. Therefore, assuming \$1080 per year (for each turbine) in maintenance costs throughout a ten-year life cycle, and compatible heat exchangers for about \$400 each, the cost of the cogeneration system, C_{COG}, would be equivalent to \$1685.7/kW (see Appendix B).

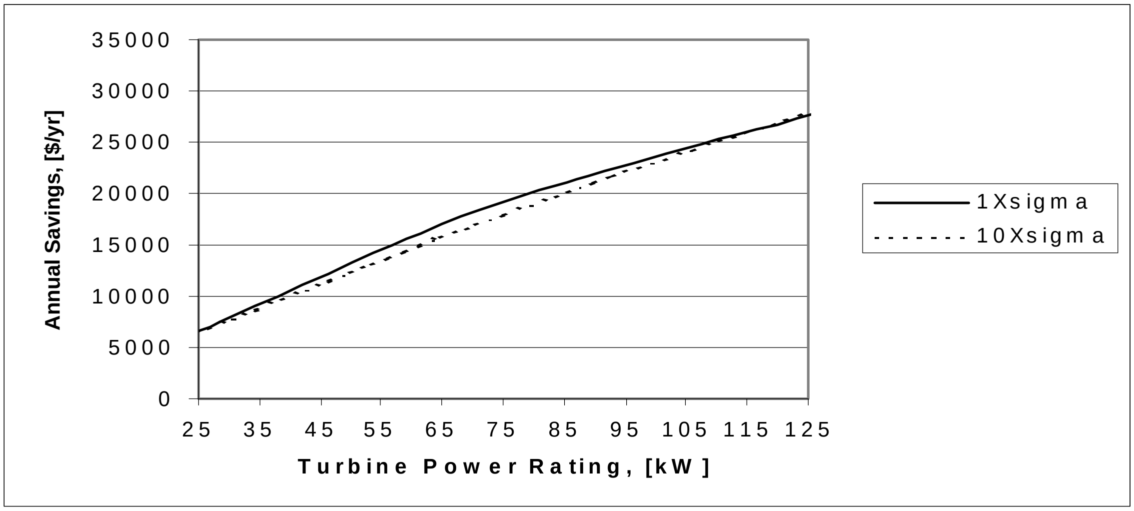

Figure 6-8a: Net Annual Savings

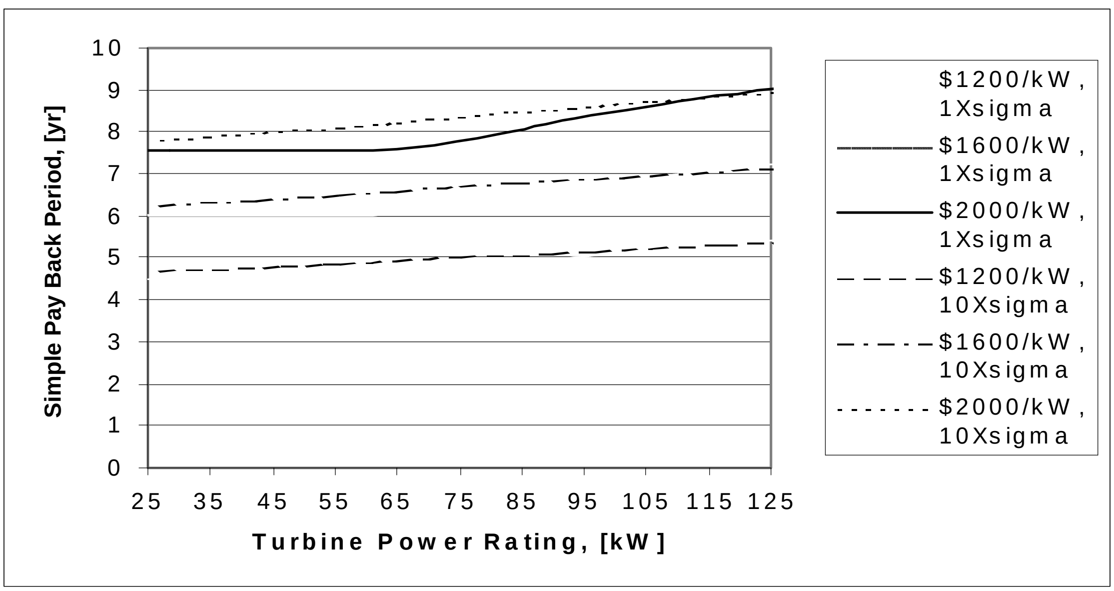

Figure 6-8b: Simple Pay Back Period

The simple pay back period is found by linear interpolation in Figure 6-8b to be 6.4 years both for a system comprised only of one turbine and for a system comprised of two turbines, 6.8 years for three turbines and 7.4 years for four turbines. Although the simple pay back period is shorter for smaller cogenerator systems, it is probably best in this case that a three-turbine system be implemented at the facility. The difference between the pay back period for a one or two-turbine system and a three-turbine system is less than five months. Figures 6-5 and 6-6 show that only having tw cogenerators would not satisfy a significant amount of the health club's hot water needs.

If the system were only comprised of one or tw cogenerators, it would be run at the maximum load factor of 0.625, without back-up. Figure 6-9 demonstrates this by showing the hours of runtime per year and the equivalent load factor plotted with the power rating of the cogeneration system. The equivalent load factor is an annual average, based on the annual runtime calculated in equation (6.2). The pay back periods for the one and two-turbine systems are equal because their annual runtimes are equal. If the thermal demand of the facility was so large that a third cogenerator would also be run at the maximum load factor, then the three-turbine system would also have a simple pay back period of 6.4 years. As it is, a third cogenerator would not need to be run during all business hours and hence could also serve as a back-up for the other two. A three-turbine system could satisfy nearly all of the facility's hot water needs. A fourth cogenerator would probably be excessive. It would rarely be run, and it adds over seven months to the pay back period over a three-turbine system.

The 84-kW micro-cogeneration system runs 4560 hours per year (see Figure 6-9). The amount of electricity produced by this system is found by means of equation (6.3) to be 383,000 kW-hr. The net annual savings of the cogeneration system is $20,800 (see Figure 6-8a). Dividing the net annual savings, $20,800, by the amount of electricity

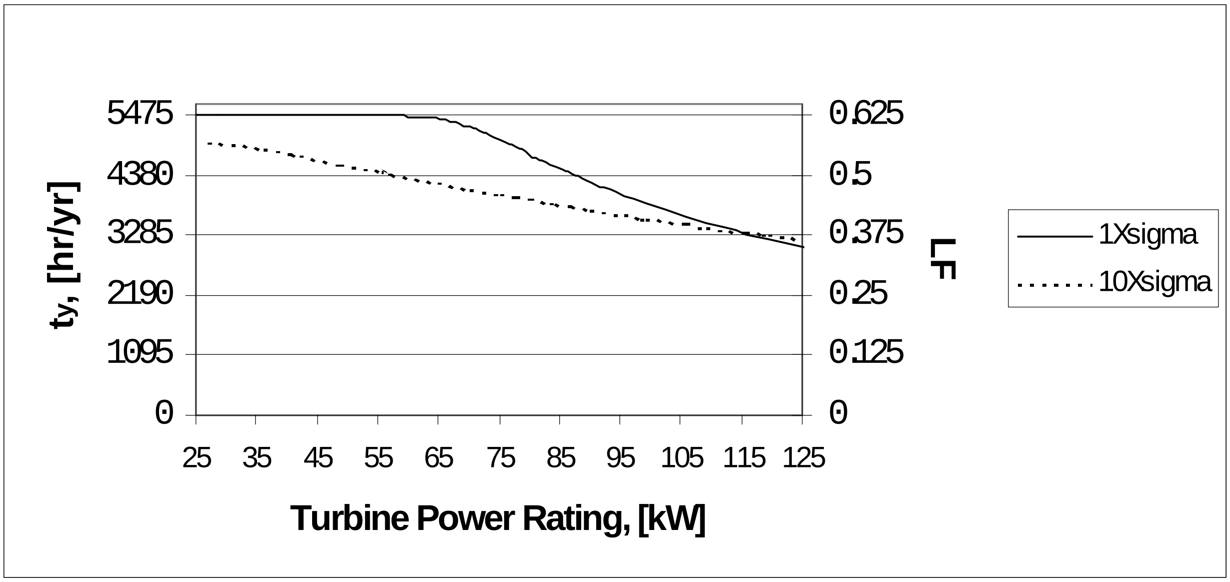

Figure 6-9: Annual Runtime of Cogeneration System

produced, 383,000 kW-hr, gives the net average savings from the electricity that was generated from natural gas instead of having been purchased from the utility. That net savings is $0.0543/kW-hr that was produced by the cogenerator, instead of being purchased. The value of the electricity produced equals the sum of the net savings and the cost of the natural gas purchased to generate that electricity, which conceptually can be seen by solving equation (6.9) for $\$_{E,COG,Y}$. The cost of natural gas is $3.40/MBtu. Converting units and adding 7% sales tax, the cost of natural gas is $0.0124/kW-hr of electricity produced by the cogeneration system. Adding that to $0.0543/kW-hr gives the average value of the electricity produced by the cogenerator, instead of being purchased from the utility, which comes to $0.0667/kW-hr.

It was noted earlier that the club would save $20,800 per year in utility costs throughout the three-turbine cogeneration system's life. This is approximately 9.5% o their current utility costs and corresponds to an internal rate of return on the investment[15] (IRRI) of 9.73%, assuming the cogeneration system lasts 10 years (see Appendix B). The IRRI is for systems that have longer lives. Further, 10 years is a very low estimate for the life of a turbine. These types of system components can last anywhere from 10 to 34 years[1]. If the turbine's life is assumed to be 15 years instead of 10, the same calculation yields an IRRI of 13.8%. If the life of the system is 20 years, the IRRI becomes 15.1%.

Another way to increase the IRRI is to finance some of the capital investment at a lower APR (Annual Percentage Rate) than the original IRRI [15]. For example, if 80% of the capital investment were financed over a 10 year period at an interest rate of 7% APR, the IRRI for the system that lasts 10 years would be 19.5% (see Appendix B). Again, the longer the system lasts, the higher the IRRI.

Environmental Impact

The carbon emissions reduction [5] can be found on an annual basis using the concepts presented in equations (3.14) and (3.15) simply by converting to the desired units. It was found that if the facility purchased the 84-kW cogeneration system, their carbon emissions would be reduced by 46.7 tons per year (see Figure 6-10). Note again that the curve changes when σ_{LN} is multiplied by ten.

Environmental and Economic Impact Combined

It is now clear that when viewed as a means for reducing carbon emissions the cogeneration system is associated with an economic benefit, i.e., profit instead of cost.

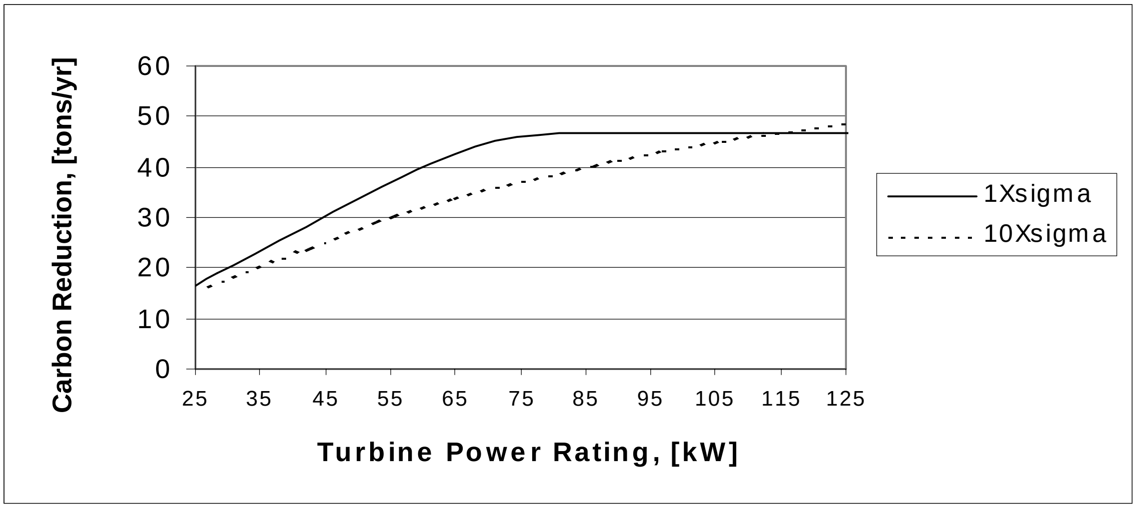

Figure 6-10: Carbon Emissions Reduction

The profit of each ton of carbon reduced, like the IRRI, is larger for longer-lasting systems. Using an interest rate of 7.5% to represent the time value of money[15], it was found that for a system that lasts 10 years, the profitability of emissions reduction is $35.32 per ton of carbon. It is $111.08 per ton for a 15-year system and $146.51 per ton for a 20-year system (see Appendix B). Note that these are positive numbers. Studies have calculated that carbon emissions reductions cost $100-200 per ton[13]. These studies did not consider the recent developments in technology which make cogeneration systems possible for commercial, as well as residential, applications. Instead of costing $100-$200 per ton of carbon emissions reduction, a profit in a similar range is made.

Discussion

The micro-cogeneration energy system brings both environmental and economical benefits to the consumer. However, the decision to invest in the system is also influenced by the pay back period. This pay back period partly depends on the standard deviation of the statistical distribution of the thermal load. Businesses generally will not invest in equipment if its pay back period is longer than two or three years.

It may seem on the surface that the power industry would suffer if a cogeneration revolution occurred. In fact, this is not the case. Energy demands increase every year because of natural economic and population growth. If some of the increasing power demand were met by dispersed power generation, central utility power providers would not have to invest in new capacity quite as quickly.

Government provides incentives for certain industries that benefit national interests. The environment has become a high international priority. Energy consumption can be lowered as a result of these incentive programs. Incentives such as tax credits could motivate more business and home owners to install cogeneration energy systems. Deregulation also may have a significant impact as more states begin to permit their residents and businesses to generate and sell power, rather than being required to purchase all of their electricity from regulated power utilities.

The problem remains however of informing energy consumers of cogeneration technology. Infomercials, newsletters, radio announcements and any other form o communication that people would not have to purchase or subscribe to can accomplish this. Once informed, some persons would take some time to investigate and decide to take advantage of this new micro-turbine technology that benefits both the nationa economy and the environment.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The economics of cogeneration systems using new micro-turbine technologies can be attractive under certain circumstances. The simple pay back period of a cogeneration energy system is shorter when the cost of electricity is higher and when the load factor of the system is increased. For example, if the cost of gas is $3.40/MBtu, the cost of electricity is $0.10/kW-hr and the cost of the cogenerator is $1600/kW, then the product of the load factor and the simple pay back period is 2.1 years. For a load factor o one, the simple pay back period is 2.1 years. For a load factor of 0.5, the simple pay back period is 4.2 years.

This study showed that more diversified thermal demand profiles result in lower utility savings and longer simple pay back periods. This means that the smaller the standard deviation, the better the economic characteristics of the system. This makes sense because for a more widely varying thermal load, the cogenerator runtime per year is less. The break-even point for economically running the cogenerator was found to be $0.0116/kW-hr. Therefore, as long as electricity costs more than that, it is profitable to run the cogenerator. When the cogenerator runtime is decreased, costly equipment sits idle when it could have been producing savings.

Large athletic clubs would benefit economically from implementing new cogeneration technology. Taking the Athletic Club Northeast in particular, three 28-kW micro-turbine generators with exhaust heat recovery would satisfy over 95% of their water heating needs, and supplement their electrical needs. Producing some of their own electricity decreases the amount of electricity purchased, thereby decreasing the electricity costs. At the same time, the environment would benefit from the decrease in carbon dioxide emissions.

The simple pay back periods for cogeneration systems in the facility studied consisting of one, two, three and four turbines were found to be 6.4, 6.4, 6.8 and 7.4 years, respectively. However, it was also found that a system consisting of only one or two turbines would not satisfy a significant portion of this facility's hot water demand. The thermal output of a four-turbine system far exceeds the thermal demand and would be redundant. It appears the best economic tradeoff for this facility to use three 28-kW micro-turbine generators.

By implementing a cogeneration system, the facility does not need to purchase as much electricity. Because of the way Georgia Power's electric rate structure is set up, this results in an effective increase of the average cost of the electricity purchased by the facility. The peak demand of the purchased electricity is lowered, but not as much as the average usage is lowered. The electric rate structure favors larger high load factor electricity purchase. The more electricity is purchased, the cheaper it becomes. However, the facility saves so much on electricity by running the cogenerator, even though what they do purchase has a higher average rate, the benefits of the cogeneration system more than compensate for the increase in the amount of natural gas purchased from running i instead of the water heaters. The fuel cost for the on-site generated electricity is only \$0.0124 per kW-hr while the avoided electricity purchased would have cost \$0.0667 per kW-hr.

This analysis also demonstrated that carbon emissions reduction could be profitable when accomplished by means of new technologies, such as small gas turbines. In the United States, 55.74% of electric power generation is fueled by coal, which emits 57 lb C/MBtu whereas natural gas only emits 32 lb C/MBtu. Further, utilities waste energy at a central site by rejecting the thermal energy in the exhaust to their surroundings. Reducing carbon emissions by means of cogeneration results in a profit of \$146.51 per ton if the system lasts 20 years. The profit is higher if the system life is longer. It is much better for economics, for fuel resource conservation and for global warming control to decentralize power generation.

Recommendations

Other industries, such as food service facilities, laundry facilities and hotels, would benefit by implementing systems of the power rating that would best suit thei thermal, electrical or economic demand, whichever operating strategy is found to be optimal. The statistical analyses performed in this study can be applied to any facility to determine the economic benefits versus the size of the cogeneration energy system.

It is also interesting to note that during the time of this study, the cost of small gas turbines went down. This probably is representative of future trends in industry. As time goes by and the cost of a small gas turbine decreases, the economic benefits of the cogeneration system will continue to improve.

The economic benefits of the cogeneration system would also be better in places where the cost of electricity is higher, such as New York and California. Facilities in those areas would definitely profit from cogeneration technology.

APPENDIX

ENGINEERING CALCULATIONS

Natural Gas-Fired Water Heater

Load Factor

Below is a calculation of the load factor of the facility's natural gas-fired water heaters. ACN has 2 water heaters. Each heater has an energy input, Q, of 1 MBtu/hr. Assume:

1. T_H = 120 °F
2. T_C = 64 °F
3. V_W = 20,000 gal/day for both heaters, i.e., 10,000 gal/day each
4. η_{WH} = 0.70

$$\eta_{WH} LF \times Q = \rho_W V_W C_{P,W} \Delta T_W$$

Solve for LF:

$$LF = \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_{WH} Q}$$

$$LF = \frac{998\left[\frac{kg}{m^3}\right]10{,}000\left[\frac{gal}{day}\right]4.18\left[\frac{kJ}{kg-K}\right](120-64)[R]}{0.70 \times 1{,}000{,}000\left[\frac{Btu}{hr}\right]264.2\left[\frac{gal}{m^3}\right]1.0551\left[\frac{kJ}{Btu}\right]1.8\left[\frac{R}{K}\right]15.0\left[\frac{hr}{day}\right]}$$

The unit conversion 15.0 hr/day comes from the average number of business hours per day.

$$LF = 0.445$$

This translates to 6.68 hours of runtime per day for each water heater.

Capacity

Below is a calculation of how much hot water the water heaters are capable o producing. Each water heater holds 500 gallons of hot water. If the water heaters run during all business hours, i.e., 15.0 hr/day, calculate V_W for each heater as follows:

$$V_W = \frac{\eta_{WH} Q}{\rho_W C_{P,W} \Delta T_W}$$

$$V_W = \frac{0.70 \times 1{,}000{,}000 \left[\frac{Btu}{hr}\right] 264.2 \left[\frac{gal}{m^3}\right] 1.0551 \left[\frac{kJ}{Btu}\right] 1.8 \left[\frac{R}{K}\right]}{998 \left[\frac{kg}{m^3}\right] 4.18 \left[\frac{kJ}{kg-K}\right] 56 [R]}$$

$$V_W = 1503.5 \left[\frac{gal}{hr}\right]$$

or

$$V_W = 1503.5 \left[\frac{gal}{hr}\right] 15.0 \left[\frac{hr}{day}\right]$$

$$V_W = 22{,}550 \left[\frac{gal}{day}\right]$$

or

$$V_W = \frac{1503.5\left[\frac{gal}{hr}\right]}{60\left[\frac{\min}{hr}\right]}$$

$$V_W = 25.1\left[\frac{gal}{\min}\right]$$

For two heaters, this translates to 50.2 gal/min of capacity, or as shown above 45,100 gal/day. The two heaters exceed the water heating requirements of the health facility.

Natural Gas Usage Distributi

The monthly gas usage records [2] and the properties of the facility's equipment were used to determine an approximate distribution of their gas usage. According to the records provided by the Atlanta Gas Light Company, the significant changes in monthl natural gas usage occur between May and June for the transition from winter to summer and between October and November for the transition from summer to winter[2].

According to the utility records[2], the average summer gas usage at ACN was 4615 ccf per month, which is equivalent to:

$$\frac{4615\left[\frac{ccf}{mo}\right]}{30\left[\frac{day}{mo}\right]} = 153.8\left[\frac{ccf}{day}\right]$$

The average winter gas usage was 8251 ccf/mo, or 275.0 ccf/day. The total annual, or overall average gas usage was 6736 ccf/mo, which is 224.5 ccf/day.

Dryer

The thermal energy input to the dryers and the heating value of natural gas were used to find out how much natural gas the dryers use. The thermal energy input to a dryer is 180,000 Btu/hr. The heating value[2] of natural gas is 102,800 Btu/ccf.

Assume:

1. Average cycle length is 40 minutes.
2. An average of 60 towels are dried in each cycle.
3. An average of 900 towels are dried each day. This assumption is based on an approximate average number of people who attend the club each day each using one towel.

$$V_{NG} = \frac{Q}{HV_{GAS}}$$

$$V_{NG} = \frac{180{,}000\left[\frac{Btu}{hr}\right]40\left[\frac{\min}{cycle}\right]1\left[\frac{towel}{person}\right]900\left[\frac{people}{day}\right]}{102{,}800\left[\frac{Btu}{ccf}\right]60\left[\frac{\min}{hr}\right]60\left[\frac{towels}{cycle}\right]}$$

$$V_{NG} = 17.5\left[\frac{ccf}{day}\right]$$

$$Summer: \frac{17.5}{153.8} = 11.4\%$$

$$W\text{int}\,er: \frac{17.5}{275.0} = 6.36\%$$

$$Overall: \frac{17.5}{224.5} = 7.80\%$$

Washer Water Heat

Below is an estimate of how much natural gas is used for the washing machines. The washing machines use 120 gallons of water for each cycle, 70% of which is heated to 120 °F.

Assume:

1. Approximately 80 towels are washed in each cycle.

2. $\eta_{WH} = 0.70$

3. $T_C = 63.8$ °F

$$V_{NG} = \frac{Q}{HV_{GAS}}$$

$$= \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_{WH} HV_{GAS}}$$

$$V_{NG} = \frac{998\left[\frac{kg}{m^3}\right]0.70\times120\left[\frac{gal}{cycle}\right]4.18\left[\frac{kJ}{kg-K}\right](120-63.8)[R]900\left[\frac{towels}{day}\right]}{0.70\times102{,}800\left[\frac{Btu}{ccf}\right]264.2\left[\frac{gal}{m^3}\right]80\left[\frac{towels}{cycle}\right]1.8\left[\frac{R}{K}\right]1.0551\left[\frac{kJ}{Btu}\right]}$$

$$V_{NG} = 6.14\left[\frac{ccf}{day}\right]$$

$$Summer: \frac{6.14}{153.8} = 3.99\%$$

$$W\text{int}\,er: \frac{6.14}{275.0} = 2.23\%$$

$$Overall: \frac{6.14}{224.5} = 2.73\%$$

Shower Water Hea

The water usage records [4] were used in conjunction with the natural gas usage records[2] to determine how much gas is used to heat shower water. Approximately 20,000 gallons of water are consumed every day at ACN. To find how much of that water is used in the showers, subtract the amount used in the washing machines.

$$\text{washer water consumed} = \frac{120\left[\dfrac{gal}{cycle}\right]900\left[\dfrac{towels}{day}\right]}{80\left[\dfrac{towels}{cycle}\right]}$$

$$= 1350\left[\frac{gal}{day}\right]$$

$$\text{shower water consumed} = 20{,}000 - 1{,}350 = 18{,}650\left[\frac{gal}{day}\right]$$

The temperature rise of the water, ΔT_W, was approximated as 40 °F.

$$V_{NG} = \frac{Q}{HV_{GAS}}$$

$$= \frac{\rho_W V_W C_{P,W} \Delta T_W}{\eta_{WH} HV_{GAS}}$$

$$V_{NG} = \frac{998\left[\dfrac{kg}{m^3}\right]18{,}650\left[\dfrac{gal}{day}\right]4.18\left[\dfrac{kJ}{kg-K}\right]40[R]}{0.70\times 102{,}800\left[\dfrac{Btu}{ccf}\right]264.2\left[\dfrac{gal}{m^3}\right]80\left[\dfrac{towels}{cycle}\right]1.8\left[\dfrac{R}{K}\right]1.0551\left[\dfrac{kJ}{Btu}\right]}$$

$$V_{NG} = 86.2\left[\frac{ccf}{day}\right]$$

$$Summer: \frac{86.2}{153.8} = 56.1\%$$

$$Winter: \frac{86.2}{275.0} = 31.4\%$$

$$Overall: \frac{86.2}{224.5} = 38.4\%$$

Spa and Pool Hea

The amount of Spa and Pool Heat natural gas consumption was assumed to be the remainder of the average summer usage.

$$V_{NG} = 153.8 - (17.5 + 6.14 + 86.2) \left[\frac{ccf}{day}\right]$$

$$V_{NG} = 44.0 \left[\frac{ccf}{day}\right]$$

$$Summer: \frac{44.0}{153.8} = 28.6\%$$

$$Winter: \frac{44.0}{275.0} = 16.0\%$$

$$Overall: \frac{44.0}{224.5} = 19.6\%$$

Building Space Hea

For the calculation of Building Space Heat, it was assumed that the Overall Building Space Heat was the remainder of the overall average usage and likewise for the Winter calculation. No Building Space Heat is needed during the summer months.

Summer: 0%

$$Winter: \frac{275.0 - 153.8}{275.0} = 44.1\%$$

$$Overall: \frac{224.5 - 153.8}{224.5} = 31.5\%$$

APPENDIX B

FINANCIAL CALCULATIONS

Internal Rate of Return on Investment

Each 28-kW micro-turbine generator [3] costs $36,000. The cost of a hea exchanger[14] is approximately $400. Assume that maintaining the turbines approximatel costs 3% per year of their original cos [1]. Maintenance of the heat exchangers is negligible because they have no moving parts.

$$3\% (\$36{,}000) = \$1{,}080 \text{ per year}$$

$$\$1{,}080 (10 \text{ years}) = \$10{,}800$$

$$\$36{,}000 + 400 + 10{,}800 = \$47{,}200$$

$$\frac{\$47{,}200}{28kW} = \frac{\$1685.70}{kW}$$

The Simple Pay Back Period for an 84-kW system is found on Figure 6-8b, using $1685.70/kW, to be 6.8 years. This means that three turbines and three heat exchangers would be purchased. Figure 6-8a shows the annual utility savings to be $20,800. To find the internal rate of return on the investment (IRRI), use the following equation[15]:

Initial Investment + (Net Annual Savings)(P/A, IRRI, Y) = 0

where Y is the number of years that the system is assumed to last. Then the Discrete Compounding tables[15] must be used to obtain P/A factors and these must be interpolated with their respective interest rates to find the IRRI. Typical system components last from 10 to 34 years[1]. Therefore, it is reasonable to calculate benefits over possible turbine lives of 10, 15 and 20 years. Using the cost of three turbines and therefore tripling the cost o maintenance:

$$\$109{,}200 + (20{,}800 - 3{,}240)(P/A, IRRI, Y) = 0$$

$$(P/A, IRRI, Y) = 6.219$$

Note that this equation yields the actual pay back period[15] of the investment, 6.2 years. The Discrete Compounding tables report the following:

$$(P/A, 9\%, 10) = 6.4177 \text{ and } (P/A, 10\%, 10) = 6.1446$$

$$(P/A, 12\%, 15) = 6.8109 \text{ and } (P/A, 15\%, 15) = 5.8474$$

$$(P/A, 15\%, 20) = 6.2593 \text{ and } (P/A, 18\%, 20) = 5.3527$$

Therefore, linearly interpolating between P/A factors at Y = 10 years yields the following results:

$$\frac{IRRI - 9\%}{10\% - 9\%} = \frac{6.219 - 6.4177}{6.1446 - 6.4177}$$

$$IRRI = 9.73\%$$

Interpolating between P/A factors at Y = 15 years gives an IRRI of 13.8%, and at Y = 20 years the rate of return is 15.1%.

<u>Partial Loan wit Ten-Year Life</u>

If 80% of the initial investment is borrowed at an interest rate higher than 9.73%, assuming the life of the turbine is 10 years, then the value of IRRI will decrease.

Contrarily, if a loan is borrowed at a lower interest rate, the IRRI will increase [15]. For an 84-kW system,

$$20\%(\$109{,}200) + (20{,}800 - 3{,}240 - \text{loan payment})(P/A, IRRI, 10) = 0$$

Using a sample loan interest rate of 7%,

$$(A/P, 7\%, 10) = 0.1424$$

And,

$$\text{loan payment} = 80\%(\$109{,}200)(A/P, 7\%, 10)$$

$$= 80\%(\$109{,}200)(0.1424)$$

$$= \$12{,}440.06$$

Also,

$$(P/A, IRRI, 10) = 4.266$$

Interpolating between (P/A, 18%, 10) = 4.4941 and (P/A, 20%, 10) = 4.1925 gives the result for this scenario, IRRI = 19.5%.

Profit from Emissions Reduction

Figure 6-10 shows that an 84-kW cogeneration system reduces carbon emissions by 46.7 tons of carbon per year. To find out how much is saved while reducing emissions, the equivalent annual savings[15] of the system must be found to compare with the emissions reduction. This is the same as assuming that the entire cost of the cogeneration system is borrowed. Using an interest rate of 7.5% for the hypothetical loan,

$$\text{loan payment} = \$109{,}200(A/P, 7.5\%, Y)$$

The A/P factors are found in the aforementioned Discrete Compounding tables[15]. A 10-year loan results in annual payments of $15,910.44. A 15-year loan costs $12,372.36 per year and a 20-year loan costs $10,717.98 per year. The loan payments are subtracted from the annual savings minus maintenance costs to obtain the net equivalent annua savings:

$$\$20,800 - 3,240 - \text{loan payment} = \text{equivalent annual savings}$$

For the 10-year assumption, the equivalent annual savings is $1649.56, for the 15-year assumption it is $5187.64 and for the 20-year assumption $6842.02. Dividing each of these by 46.7 tons of carbon per year results, respectively, in profits of $35.32, $111.08 and $146.51 per ton of carbon over a 10-year, 15-year and 20-year life.

APPENDIX C

ELECTRIC RATE STRUCTURE

The following is the rate structure[7] Georgia Power uses to calculate ACN's electric bill.

Base Charge: $16.75 per month

All consumption (kWh) not greater than 200 hours times the billing demand:

First 3,000 kWh:	$0.10900 per kWh
Next 7,000 kWh:	$0.09988 per kWh
Next 190,000 kWh:	$0.08600 per kWh
Over 200,000 kWh:	$0.06670 per kWh

All consumption (kWh) in excess of 200 hours and not greater than 400 hours times the billing demand: $0.01110 per kWh

All consumption (kWh) in excess of 400 hours and not greater than 600 hours times the billing demand: $0.00836 per kWh

All consumption (kWh) in excess of 600 hours times the billing demand:

$0.00732 per kWh

(Note, however, ACN's consumption did not exceed 600 hours times their billing demand in the past year.)

The Billing Demand is based on the highest 30-minute kW measurement during the current month and the preceding 11 months. For the billing months of June through September, the Billing Demand shall be the greatest of:

1. The current actual demand

2. Ninety-five percent of the highest actual demand occurring in any previous applicable summer month (June through September)

3. Sixty percent of the highest actual demand occurring in any previous applicable winter month (October through May)

During the billing months of October through May, the Billing Demand shall be the greater of:

1. Ninety-five percent of the highest summer month (June through September)

2. Sixty percent of the highest winter month (October through May), including the current month

All bills rendered subject to the Fuel Recovery Schedule shall be respectively increased in an amount equal to $0.013994 per kWh for Secondary Distribution customers, $0.013722 per kWh for Primary Distribution customers and $0.013548 per kWh for transition customers. (Note, ACN is a Secondary Distribution customer.)

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