Optimizing operation of a campus energy system for economic and environmental considerations

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OPTIMIZING OPERATION OF A CAMPUS ENERGY SYSTEM
FOR ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

by
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Dedication

I would like to dedicate this manuscript to my spouse Lisa Ann Imperatore, and children Alyssa, Tara, Christopher, and Tommy for their love and support each step of the way throughout this process. I would also like to dedicate this manuscript to my mother MaryAnn Hartman and husband Robert Hartman for their encouragement, love, and support, with special recognition to my mother for her endless ambition, inspiration, and pride throughout my life.
Acknowledgments

I would like to express my appreciation to Professor William T. Riddell for his unrelenting patience, many hours of tireless guidance, and continuous encouragement throughout this research.
The objective of this thesis is to determine effective costs of campus utilities, optimal operation of energy conversion and production subsystems through minimization of economic and environmental costs, and to evaluate how changing electrical grid costs and sources will affect future optimal operations at a campus. Characteristic days were developed to typify campus activities and their impact on energy consumption. At current grid electricity and natural gas prices, utilization of a cogeneration unit, a form of combined heat and power plant, is less expensive than purchasing equivalent amounts of electric and gas to produce steam, as long as there is sufficient campus demand for the electricity and steam produced. Carbon dioxide emissions during cogeneration unit operation was nearly the same as purchasing equivalent amounts of electric and gas to produce steam. Simulation of economic and environmental performance of the cogeneration plant, found minor differences between least expensive and greenest operations. Analyses suggested that grid emissions will not become clean enough to merit decommissioning of cogeneration plant early. Operation of the cogeneration plant is favorable for economical and environmental considerations.
# Table of Contents

Abstract v

List of Figures ix

List of Tables xi

Chapter 1: Introduction and Scope 1

Chapter 2: Literature Review 5

Chapter 3: Analysis of Campus Utilities Economic and Environmental Cost 13

3.1 Overview of Campus Energy System, Circa 2007 13

3.2 Description of Overall Energy Delivery System to Campus 14

3.3 Primary Level Utilities 16

3.4 Plant Description and Primary Plant Level Equipment 17

3.5 Secondary Plant Level Equipment 21

3.6 Available Utilities 22

3.7 Campus Energy Usage 24

3.8 Energy Stream Reference Indices 26

3.9 Purchased Electricity Streams 29

3.9.1 Energy Distribution, Quantification, and Analysis 31

3.9.2 CO2 Emissions Distribution and Quantification 35

3.9.3 CO2 Quantities per Unit of Host Energy 38

3.9.3 Campus Infrastructure Changes – Circa 2009 45
# Table of Contents

Chapter 4: Period of Study and Campus Energy Systems 47  
4.1 Period of Study 47  
4.2 Sources of Data 48  
4.3 Campus Energy Systems 50  
4.4 Campus Energy Consumption and Demand 55  

Chapter 5: Optimization Approach and Analysis 61  
5.1 Developing Characteristic Days 61  
5.2 Establishing Parameters 70  
5.2.1 Efficiencies of Units 70  
5.2.2 Cost and Emissions for Natural Gas and Electricity 73  
5.2.3 Algorithm for Analysis 80  

Chapter 6: Optimized Operations 86  

Chapter 7: Results and Discussion 96  
7.1 Point in Time Analysis -- Economics 96  
7.2 Economic Break-Even Point 100  
7.3 Point in Time Analysis – Environmental Impacts 103  
7.4 Environmental Break-Even Point 106  
7.5 Simulations based on Characteristic Days 109  
7.6 Sensitivity Analysis 114
## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7 Reliability and Emergency Preparedness</td>
<td>125</td>
</tr>
<tr>
<td>Chapter 8: Summary and Conclusions</td>
<td>127</td>
</tr>
<tr>
<td>List of References</td>
<td>136</td>
</tr>
<tr>
<td>Appendix A: Computer Programming Code</td>
<td>138</td>
</tr>
<tr>
<td>Appendix B: Primary Plant Equipment Specifications</td>
<td>148</td>
</tr>
</tbody>
</table>
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 3.1 Overall Central Heat and Power Plant Schematic – Circa 2007</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.2 Overall Campus Energy Flow Schematic</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.3 Identification of all Energy Streams</td>
<td>29</td>
</tr>
<tr>
<td>Figure 3.4 Electricity purchased by Rowan University by Energy Source</td>
<td>31</td>
</tr>
<tr>
<td>Figure 3.5 Supply and Demand Energy Accounting – FY07</td>
<td>32</td>
</tr>
<tr>
<td>Figure 3.6 Quantification of CO2 Emissions</td>
<td>37</td>
</tr>
<tr>
<td>Figure 3.7 CO2 Emissions Quantities per Unit</td>
<td>39</td>
</tr>
<tr>
<td>Figure 4.1 Schematic of Typical Cogeneration Unit</td>
<td>51</td>
</tr>
<tr>
<td>Figure 4.2 Schematic of Water-tube Boiler Economizer</td>
<td>55</td>
</tr>
<tr>
<td>Figure 4.3 Campus Electric Demand, kW versus Hour</td>
<td>56</td>
</tr>
<tr>
<td>Figure 4.4 Campus Electric Load Duration Curve</td>
<td>58</td>
</tr>
<tr>
<td>Figure 4.5 Campus Steam Demand</td>
<td>57</td>
</tr>
<tr>
<td>Figure 4.6 Campus Steam Load Duration Curve</td>
<td>58</td>
</tr>
<tr>
<td>Figure 5.1 Generalized Flowchart for Optimization Program</td>
<td>81</td>
</tr>
<tr>
<td>Figure 6.1 Campus Electric Load Duration Curve</td>
<td>88</td>
</tr>
<tr>
<td>Figure 6.2 Campus Electric Load Duration Curve with Stacked Energy Sources</td>
<td>89</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 6.3 Campus Electric Load Duration Curve</td>
<td>90</td>
</tr>
<tr>
<td>Figure 6.4 Campus Steam Load Duration Curve</td>
<td>91</td>
</tr>
<tr>
<td>Figure 7.1 Decision Matrix for Plant Operation</td>
<td>109</td>
</tr>
<tr>
<td>Figure 7.2 Annual Cost Differences for Optimal Operation</td>
<td>114</td>
</tr>
<tr>
<td>Figure 7.3 Cost Differences – Overall Transition Areas</td>
<td>116</td>
</tr>
<tr>
<td>Figure 7.4 Cost Differences – First Transition Area</td>
<td>117</td>
</tr>
<tr>
<td>Figure 7.5 Cost Differences – Second Transition Area</td>
<td>118</td>
</tr>
<tr>
<td>Figure 7.6 Differences in annual CO$_2$ emissions between</td>
<td>119</td>
</tr>
<tr>
<td>Figure 7.7 Annual CO$_2$ Emissions Differences</td>
<td>120</td>
</tr>
<tr>
<td>Figure 7.8 Cost per Pound of CO$_2$ Emissions</td>
<td>121</td>
</tr>
<tr>
<td>Figure 7.9 Interagency Working Group Comparison</td>
<td>122</td>
</tr>
<tr>
<td>Figure 7.10 CO$_2$ Emissions Cost – First Transition Area</td>
<td>123</td>
</tr>
<tr>
<td>Figure 7.11 CO$_2$ Emissions Cost – Second Transition</td>
<td>124</td>
</tr>
<tr>
<td>Area Figure 8.1 Historical and Projected Electricity Costs</td>
<td>134</td>
</tr>
</tbody>
</table>
List of Tables

Table | Page
-----|-----
Table 2.1 Social Cost of CO₂ | 6
Table 3.1 Determination of CO₂ emissions coefficients – Cogeneration Unit | 42
Table 3.2 Determination of CO₂ emissions coefficients – Overall Plant | 44
Table 4.1 Excerpt of Plant Steam and Electricity Production Data | 49
Table 4.2 Excerpt of Quarter-Hour Interval Data | 50
Table 4.3 Capacities of Cogeneration Units and Boilers | 55
Table 4.4 Comparison of Plant Input Energies for FY2006 | 59
Table 4.5 Conversions of Plant Output Energies | 60
Table 4.6 Preliminary Determinations of CO₂ Emissions Coefficients | 60
Table 4.7 Final Determinations of CO₂ Emissions Coefficients | 60
Table 5.1 Excerpt of Table Showing Campus Steam and Electricity Production | 63
Table 5.2 Academic Characteristic Days | 64
Table 5.3 Excerpt of table Showing Assigned Academic Characteristic Days | 65
Table 5.4 Table of Energy Characteristic Days | 67
Table 5.5 Energy Characteristic Day Model | 68
Table 5.6 Simulation of Characteristic Day Model | 69
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5.7 Coefficients – Quantities of Electricity and Steam</td>
<td>71</td>
</tr>
<tr>
<td>Table 5.8 Economic and Environmental Coefficients</td>
<td>80</td>
</tr>
<tr>
<td>Table 7.1 Summary of CO$_2$ Emissions and Costs</td>
<td>103</td>
</tr>
<tr>
<td>Table 7.2 Cost and CO$_2$ Emission values -- Economic</td>
<td>111</td>
</tr>
<tr>
<td>Table 7.3 Cost and CO$_2$ Emission values -- Environmental</td>
<td>112</td>
</tr>
<tr>
<td>Table 7.4 Optimized Economic and Environmental Costs</td>
<td>113</td>
</tr>
<tr>
<td>Table 8.1 Campus Electricity and Steam Usages</td>
<td>127</td>
</tr>
<tr>
<td>Table 8.2 Purchased Utilities and CO$_2$ Emissions</td>
<td>128</td>
</tr>
<tr>
<td>Table 8.3 Potential Reconfiguration of Characteristic Days</td>
<td>130</td>
</tr>
</tbody>
</table>
Chapter 1
Introduction and Scope

This thesis focuses on energy purchasing, conversion, and production systems situated at Rowan University, a public university located in Glassboro, New Jersey. Rowan University has a complex utility (energy) system, consisting of two cogeneration units, three boilers, and three chillers that are fueled by, and supplemented with, electrical grid, natural gas, and other utility purchases. As part the overall campus energy system, in this thesis, we refer to the cogeneration units and boilers as subsystems. A cogeneration system is a form of combined heat and power energy generation. Using the term cogeneration in a campus energy system context refers to equipment utilizing combustion of natural gas or fuel oil to produce thermal energy and electrical energy simultaneously. The objective of this thesis is to determine effective costs of campus utilities, the optimal operation of energy conversion and production subsystems through minimization of economic and environmental costs, and to evaluate how changing electrical grid costs and sources will affect future optimal operations.

The optimization of electric and thermal energy generation systems is a topic of increasing importance given recent attention placed by society on economic and environmental costs of energy use. Specifically, energies in this context refer to electricity, steam, and chilled water as utilities used in industrial, commercial and residential facilities. In general, thermal and electrical energy generation and distribution systems are complex in that multiple types and numbers of energy producing and conversion equipment are integrated into networks of devices that must work in harmony.
to achieve a common objective. Traditionally, the objective has been to maximize economic performance. Given finite fossil fuel resources and growing concerns with environmental impact, there has been increased emphasis on other objectives in addition to economic. This shift in thinking has led to the emergence of minimized environmental impact as a potential additional objective. A new challenge has emerged as a result: To balance both economic costs and environmental impact. In this context, optimization refers to the minimization of either economic or environmental costs, quantified by dollars or carbon emissions, respectively. The minimization of environmental costs in this thesis refers to the minimization of carbon dioxide (CO₂) emissions from generating electricity. It is well known that the emission of CO₂ from fossil fuel-burning power plants is not the only contributor to air pollution. Other contributors to air pollution from fossil fuels include carbon monoxide, nitrous oxide, sulfur dioxide, and volatile organic compounds (VOCs). Coal-fired power plants emit sulfur dioxide. Hydraulic fracturing (fracking) is a current well drilling technology that raises concerns about contamination of ground water supplies. In the case of nuclear power generation, radioactive solid waste is an additional concern. This thesis focuses on CO₂ emissions and costs associated with operation of Rowan University’s campus energy system.

Chapter 1 introduces the topic of this thesis in a broad sense, and summarizes the scope of this study. Chapter 2 discusses results of previous efforts reported in the literature that are related to topics associated with this study.
Chapter 3 presents an overview of the Rowan University energy system, including a high level analysis of carbon dioxide (CO₂) emissions of the Rowan University campus during the year 2007, when this research was initiated. The high level analysis presents a review of major energy streams at Rowan University including utilities purchased, thermal and electrical energies produced, and utilization of energy on campus. Purchased utilities include electricity and natural gas delivered to Rowan University by outside utility providers. Produced thermal and electrical energies include steam and electricity generated and distributed by Rowan University. Chapter III also examines the environmental performance of Rowan University through an assessment of CO₂ emissions. The energy systems reviewed in this chapter include raw fossil and renewable utilities, electrical and thermal utilities generated on-site, and the consumption of utilities at end use levels.

Chapter 4 discusses the Rowan University campus energy system in 2009 following the implementation of two new cogeneration subsystems and decommissioning the previous cogeneration subsystem. In addition, an analysis of on-campus energy production and energy usage is presented for the study period. Sources of data utilized in this thesis are identified and critical parameters for modeling are established. An updated description of campus energy equipment is presented in this chapter.

Chapter 5 presents an approach for analytical optimization of operation of the energy system. A concept that characterizes energy demand through a full year of seasonal weather changes and a full range of campus activities is developed and
presented. Parameters established for optimization analysis are discussed in this chapter.

In addition, an algorithm developed for optimization is presented in this chapter.

Results from the analyses are presented in Chapter 6.

Chapter 7 presents results and discussion. In addition, Chapter VII includes a sensitivity analysis of the mathematical model developed in this thesis.

Finally, summary and conclusions can be found in Section 8. This section summarizes the key areas of focus defined in this report and identifies conclusions resulting from this study.
Chapter 2

Literature Review

This thesis discusses the optimization of a campus-based energy system comprised of two cogeneration subsystems, three steam boilers, and a chiller plant. Cogeneration systems are utilized in a variety of commercial applications involving the availability of natural gas and year-round thermal and electrical energy demands.

This chapter summarizes research that has been reported in the literature regarding the optimization of electric and thermal energy generating systems. Specifically, energy in this context refers to electricity and heat utilized in an application serving commercial and residential facilities. In this application, heat also is utilized to provide cooling through the use of steam-based absorption cooling technologies. Optimization of electric and thermal energy generating systems can take a variety of forms. This includes optimizing the performance of a single generating unit. Optimization can also refer to maximizing the overall utilization of multiple components within a large system. Optimization of energy systems in this thesis refers to assessing the performance of multiple components of an energy system from a macro approach. The macro approach refers to maximizing the performance of two cogeneration units with consideration given to the performance of three boilers and assessment of campus electric and thermal demand. This focus differs from routine tuning procedures utilized in starting up and commissioning individual equipment. This includes setup and adjustment of parameters for controllers and process pressures and temperatures, associated with micro-optimization.
The Interagency Working Group on Social Cost of Carbon\(^1\) presented a paper that estimates the social cost of carbon. The purpose of the study was to allow agencies to incorporate the social benefits of reducing carbon dioxide emissions into cost-benefit analyses of regulatory actions that impact cumulative global emissions. The social cost of carbon is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. The study updates prior efforts to monetize carbon emissions and provides tables that economically quantify the social cost of carbon in dollars per metric ton of carbon dioxide. Shown in Table 2.1 below is a social cost of carbon table that includes cost projections for years 2010 through 2050. As shown, the social cost of carbon values are presented in four different discount rate values ranging from 2.5 percent to 5.0%.

<table>
<thead>
<tr>
<th>Discount Rate</th>
<th>5.0% Avg</th>
<th>3.0% Avg</th>
<th>2.5% Avg</th>
<th>3.0% 95th</th>
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<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>11</td>
<td>33</td>
<td>52</td>
<td>90</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>38</td>
<td>58</td>
<td>109</td>
</tr>
<tr>
<td>2020</td>
<td>12</td>
<td>43</td>
<td>65</td>
<td>129</td>
</tr>
<tr>
<td>2025</td>
<td>14</td>
<td>48</td>
<td>70</td>
<td>144</td>
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<tr>
<td>2030</td>
<td>16</td>
<td>52</td>
<td>76</td>
<td>159</td>
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<tr>
<td>2035</td>
<td>19</td>
<td>57</td>
<td>81</td>
<td>176</td>
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<tr>
<td>2040</td>
<td>21</td>
<td>62</td>
<td>87</td>
<td>192</td>
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<tr>
<td>2045</td>
<td>24</td>
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</tr>
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<td>2050</td>
<td>27</td>
<td>71</td>
<td>98</td>
<td>221</td>
</tr>
</tbody>
</table>
Linear Programming has been widely used for micro energy system optimization. Linear Programming refers to the modeling of complex systems using mathematical relationships in canonical form. Such relationships are constructed around specific objectives to be achieved as well as requirements built into the problem. Typically, linear programming problems consist of an objective function to be minimized or maximized and constraint equations. The overall objective is to determine the best outcome or set of outcomes. For example, Hori, et al\textsuperscript{2}, optimized the economic operation of a gas turbine cogeneration plant. A mathematical relationship based on the standard annual cost method defined the economics of the plant. This relationship formed the objective function which was minimized. All other formulations involved system constraints serving as the conditions of the problem. Mixed-integer linear programming was used to determine the optimal combination of equipment in the plant.

Acuri, et al.,\textsuperscript{3}, also utilized Linear Programming to optimize the operation of a trigeneration system at a hospital complex. Trigeneration is the simultaneous production of heating, cooling, and electricity in one process. The goal of the optimization was to maximize short and long term investment returns for the trigeneration system. Constraints were developed after decision variables were established. Binary variables were used to describe the on/off state of the devices. Once formulated, the mathematical model was solved using a popular mathematical software program known as LINGO. As a result, a description of an optimal plant configuration was achieved.
Another approach to optimizing energy systems, Derivation-Based Systems Modeling, incorporates the use of graphical and mathematical representations for systems analysis. For system representation, a function model, also called an activity model or process model, is developed and serves as a graphical representation of a function within a defined scope. The purposes of the function model are to describe the functions and processes, assist with discovery of information needs, help identify opportunities, and establish a basis for determining system performance as defined by management policy or objectives. For example, a cogeneration plant located in Zagreb, Croatia was optimized based on economics. In this case, each energy generating and conversion device was modeled with respect to energy efficiency, energy recovery and performance. Each component model was solved according to its boundary conditions and input data. An iterative technique was used due to the nonlinear nature of several of the components. A mathematical representation was written in MS Excel Visual Basic language and solved for system optimization based on economics.

Another example of Derivation-Based Systems Modeling for energy system optimization was identified in a paper that discussed systems comprised of multiple energy carriers. Geidl and Anderson take an approach that is based on the concept of ‘energy hubs’. The perspective of energy hubs enables analysis of couplings and interactions between the different infrastructures. A generalized modeling and optimization framework for energy systems, involving multiple energy carriers, was developed. In cases where the objective function is concave and/or the constraints are nonlinear, numerical methods can be used, but it cannot be ensured that the global
optimum solution is achieved. Similar to the standard approach for electricity systems, this method incorporates a general dispatch rule for linear energy hubs and is derived and related to the marginal cost of energy carriers.

Another approach to optimizing energy systems involves an overall improvement design concept. Giannantoni et al.\(^6\) present a broad iterative procedure that expands the overall design concept to include economic and environmental considerations in addition to a typical engineering approach that focuses on design of existing energy conversion systems. The concept is based on 1.) a traditional engineering approach that focuses on energy conversions and 2.) the integration of environmental and economic assessment procedures to influence an already existing design. The procedure is presented as a concept that incorporates environmental and economic evaluations as feedback loops to the iterative design process. As opposed to traditional optimization methods that use complex algorithms and/or multi-objective functions, the methodology used here consists of a progressive step-by-step improvement of a preliminary solution, which can be modified according to the results of selected groups of indicators.

We now take a look at macro approaches to energy system optimization. Gamous, et al.\(^7\) proposed a method for evaluating the economic feasibility of microturbine cogeneration systems in typical hotel settings. The method proposed involved developing and examining mathematical relationships between the optimal number of microturbine cogeneration units and the maximum energy demands under various conditions. Based on a linear programming approach, electrical generating
efficiency and capital unit cost parameters were established, to understand their influence on the economic feasibility of the overall system. Relationships between optimal number of microturbine cogeneration units and the maximum energy demands were illustrated under various scenarios by this study.

Casisi, et al.\textsuperscript{8} presented an optimization model of a distributed cogeneration system with a district heating network in an urban environment. The overall plant under review consisted of multiple natural gas-fired micro-turbines installed in six public buildings, each with a single natural gas-fired boiler, located in Pordenone, Italy. A centralized cogeneration unit is comprised of a natural gas-fired internal combustion engine coupled to an electric generator. Electricity demand not met by the generator is supplemented by grid purchases. An objective function was selected to provide an economic optimization of annual total costs, consisting of owning, operating, and maintaining the system. A mixed integer linear program was formulated and solved by commercial software working on the basis of the classical Branch and Bound algorithm approach\textsuperscript{9} to finding optimal solutions for optimization problems. The optimization model allowed the optimal lay-out and operation of a cogeneration system to be obtained, taking into consideration technological options, year-round varying ambient conditions, fuel rates, and grid electricity rates.

Gimelli, et al.\textsuperscript{10} presented an optimal configuration of a cogeneration system in a hospital setting, using a multi-objective approach. The study was focused at S. Paolo Hospital in Naples, Italy and was structured around goals to optimize the system through
minimization of energy and economics. The study presented analyses of cogeneration applications with natural gas-fired reciprocating internal combustion engines with capacity ranges on the order of three-to-five megawatts of power. Electric and thermal loads were studied and energy characteristic weeks, broken down on daily bases, over three seasons emerged. Ten scenarios with varying combinations of cogeneration equipment type and size were evaluated using the multi-objective approach. A solution to utilize three natural gas reciprocating engines with generators in the size range of 225-240 kilowatts provided significant energy savings. It was found that this configuration produced a reasonable compromise of operational flexibility, plant simplicity, and reliability.

Yilmaz\textsuperscript{11} presents optimization of cogeneration systems based on performance criteria that differs from traditional criteria. In this study, a reversible Carnot cycle, modified for cogeneration, with external irreversibilities, is analyzed with the aid of numerical analysis. A goal of this study was to develop better performance criteria for actual cogeneration plants. This analysis incorporates exergenic performance criteria, consistent with thermodynamic and energetic studies. One of the alternative performance criteria utilized by Yilmaz is artificial thermal efficiency. The artificial thermal efficiency plays an important role in that this study assumes a cogeneration plant configured with a steam extraction turbine. It was found that when R, a power to process heat ratio, is equal to one, R becomes a critical value. By varying the source side and consuming side temperatures, energy utilization factor and exergy efficiency values also change and affect performance.
This thesis also included research and review of literature that focused on modeling of energy demand. Ortiga, et al.\textsuperscript{12} proposed a method for the selection of typical days of hourly energy demand for one year in a building. The selection of typical days enabled a reduction in the number of data points associated with 365 days a year. The typical days were characteristic of days that could be grouped for data simplification, yet repeatable to the extent that reasonable accuracy was preserved. In addition, an analysis of the influence of the results on an optimization model for a trigeneration system was prepared. The authors utilized a graphical method to accomplish these objectives. Specifically, cumulative energy demand curves were produced for select heating and cooling days that were repeatable. The cumulative energy demand curves had to be as close as possible to a cumulative energy demand curve for the entire year in review. The results were tested in previously-developed economic optimization programs. It was determined that this method worked well, provided that several of the selected days are tested so that a correct representation of a whole year can be verified.
Chapter 3

Analysis of Average Campus Utilities Economic and Environmental Cost

This chapter presents an overview of the Rowan University campus energy system in the fiscal year 2007. The environmental impact of all delivered utilities to campus buildings, including dormitories and apartments, fed from a central heat and power cogeneration plant during university business year FY07 is analyzed. Quantities of CO₂ emissions for each utility, ranging from raw to delivered utilities, were determined. This chapter also includes an assessment of the original cogeneration plant in terms of the environmental impact of the energy conversion processes for all equipment that was operational during business year FY07. The energy-related carbon footprint of the campus, its students including residential, and staff is determined in this chapter. Energy quantities associated with all purchased and produced utilities for FY07 are presented in this study. All energy quantities are converted to their equivalent CO₂ emission levels appropriate conversion factors. The results are displayed on campus energy stream flow diagrams developed for this purpose.

3.1 Overview of Campus Energy System, Circa 2007

Founded in 1923 and known at the time as a two-year teaching school called “Glassboro Normal School,” Rowan University has experienced significant growth over time and as of July 31, 2013, serves a student population of 13,349, a third of which reside on campus. Faculty and staff comprise 2,057 of the total community population of 15,406. The campus community is mainly situated on a developed parcel of land.
traversing an area of 203 acres. Approximately 2.5 million gross square feet of space is made up by 72 buildings, primarily comprised of academic, administrative, and residential facilities.

In 2007, Rowan University served a student population of 10,091, a third of which resided on campus\textsuperscript{14}. Rowan University utilized a fiscal-year system as a basis for business and financial accounting systems coincident to the State of New Jersey. Within these systems, fiscal years run from July 1 to June 30. Specifically, the period of study in this chapter commences on July 1, 2006 and runs through June 30, 2007. This period is referred to as Fiscal Year 2007 and is referred to throughout this chapter as FY07.

3.2 Description of Overall Energy Delivery System to Campus

A schematic diagram of the central heat and power plant, with its relationship to the campus, is depicted below in Figure 3.1. As shown, in FY07, the original cogeneration plant was a single 1.5 MW cogeneration unit. Further, the cogeneration unit was part of an overall energy delivery system that included purchased electric, natural gas, fuel oil, and water utilities, three steam boilers, a steam-driven centrifugal chiller, and two electrically-driven centrifugal chillers. As shown, energies delivered to campus buildings were in the form of steam, electricity, and chilled water. Note this is a graphical representation of the general arrangement of the circa 2007 central heat and power plant with relative equipment sizing shown, to acquaint the reader with a general understanding of the overall concept and function. A detailed description follows.
The combination of natural resources, purchased energy, produced energy, coupled with distribution and usage, formed a complete system of energy delivery and consumption for the Rowan University campus. This system has been classified into five categories: Primary Level Utilities, Primary Plant Level, Secondary Plant Level,
Available Utility, and Campus Use. Refer to Figure 3.2 below for detailed descriptions of these classifications.

3.3 Primary Level Utilities

The term “primary level utilities” used in this study refers to the raw resources utilized in the generation and delivery of utilities purchased by the university. With respect to purchased electricity, a breakdown of the individual components that make up
fossil and renewable generated sources and technologies has been obtained from Atlantic City Electric, the local electrical service provider. Regarding fossil fuels, Rowan University purchased electricity generated from a mixture of sources including coal, nuclear, natural gas, and oil. On the renewable portion of the mixture, technologies included solar energy, solid waste, captured methane gas, hydroelectric, wood and other biomass, and wind. In addition, the university purchased wind renewable energy certificates (w-recs) directly from a third party alternative energy generator.

Natural gas was directly purchased from Amerada Hess, a third party supplier, and delivered by South Jersey Gas, a local transportation natural gas utility. Fuel oil was purchased directly from Riggins, a local petroleum supplier.

3.4 Plant Description and Primary Plant Level Equipment

Primary plant level on-site energy generation refers to electric and heat energy generated on-site for distribution and usage by the campus. The “primary” portion of the central power plant was configured with three boilers and one combined heat and power generation unit. In 2007, a process to replace the existing 1.5 MW cogeneration unit with a 4.7 MW combined dual turbine cogeneration plant was initiated.

Two of the three boilers were manufactured by Babcock & Wilcox and were installed in 2005. The two boilers were rated each at 40,000 pounds of steam per hour. The manufacturer-supplied efficiencies of the two boilers were 83% using Natural Gas
and 81% using Fuel Oil. Efficiency, in this context, refers to the ratio of energy output divided by energy input. In the case of steam, the energy output is considered to be the increase in specific energy times mass associated with converting condensate returning from campus into steam. The third boiler was installed in 1960 and was de-rated to 26,000 pounds of steam per hour in the 1970s to comply with evolving environmental regulations. The efficiency of this boiler is approximately 75% with natural gas as a fuel. The thermal energy conditions produced by the boilers were 150 pounds per square inch of saturated steam at 366° F. Saturated steam was utilized on campus for heating, air conditioning, domestic hot water, and laboratory process applications. A detailed description of the boilers is presented in chapter 4. In general, the boilers operated in standby and supplemental capacity modes. For example, if the campus steam requirements were being met by the cogeneration unit, the boilers were put in standby mode or in a state of “readiness” for supplemental or emergency demand needs. If the cogeneration unit could not meet the campus steam requirements, the boilers were put into operation in a sequence such that the most efficient boilers were brought on line first. All three boilers could operate either on natural gas or number two fuel oil. With choices of fuel input and instrumentation, plant operators could base their fuel decisions on economy, reliability, energy efficiency, or available fuel supply. In addition, this dual-fuel arrangement also permitted switching to the second fuel whenever the first fuel was curtailed for emergency reasons. This flexibility helped the university hedge sudden fuel cost increases through fuel diversity.
The cogeneration unit produced steam and electricity simultaneously. A detailed description of cogeneration operation is presented in chapter 4. Similar to the three boilers, the cogeneration unit had dual-fuel capability utilizing natural gas or fuel oil. However, during the period chosen in this chapter, only natural gas was utilized by the cogeneration unit. This was due to an ongoing malfunction of the liquid fuel delivery system.

The original cogeneration unit employed a turbine in which a fuel/air mixture was ignited in a combustion chamber resulting in an increase in gas pressure that was expanded against turbine blades. The expansion produced thrust as the resulting chemical energy was converted into mechanical energy in the form of rotary motion produced by the turbine. The turbine was mechanically coupled to an electric generator through a gearbox and electricity was produced by a stator rotating in an excitation field. The gearbox allowed the rotational speed turndown of the turbine from 22,000 revolutions per minute to 1,800 revolutions per minute, so that the three-phase generator could deliver the proper electrical energy characteristics. The electrical output of the generator was a nominal 1.2 MW and delivered a nominal voltage of 4,160 volts.

On the thermal portion of the cogeneration unit, high temperature combusted gases were exhausted from the turbine. The combusted gases were routed from the turbine to the outside of the cogeneration unit and into a two-way bypass valve. During normal operation this valve diverted all gases into a heat recovery steam generator (HRSG). The HRSG is similar to a standard water tube boiler except for the source of
Instead of combusting natural gas or oil, high temperature turbine exhaust gases pass over tubes containing water that is converted to steam. As with the boilers, thermal energy delivered by the cogeneration unit was 150 pounds per square inch of saturated steam. In the event that the HRSG needed to be taken out of service while the cogeneration unit remained in service, the position of the two-way bypass was changed to divert all gases to the stack, venting all turbine exhaust gases directly to the atmosphere.

The 1.2 MW cogeneration unit was manufactured by Kawasaki Motors Corporation, was first put in service in 1991, and through the HRSG delivered 9,000 pounds per hour of 150 pounds per square inch saturated steam. In addition, ductburner equipment was installed for emergency heat generation. In the event that the cogeneration unit failed and there was no other source of heat available, the ductburner unit could be put into service. The ductburner was essentially a direct-gas-fired heating unit installed in the ductwork between the turbine and the HRSG unit. During emergencies, this equipment replaced the turbine exhaust to maintain a heat source for the HRSG, and was capable of generating 21,000 pounds of steam per hour on its own. According to plant operators, the ductburner was never placed on line at any given time during FY07.

As the prime mover of the Primary Plant Level, the cogeneration unit fulfilled the lead role in supplying electricity and steam to other parts of the plant and the balance of the campus. In this configuration, electricity was purchased to meet the balance of campus demand not met by the cogeneration unit. The same went for the heat side of the
cogeneration unit, as the boilers were operated as required to supplement the steam
demand not met by the cogeneration unit. Electricity and steam generated by primary
plant level equipment entered the secondary portion of the central heat and power plant.

3.5 Secondary Plant Level Equipment

Secondary Plant Level Equipment refers to equipment that was involved in the
on-site production of chilled water for distribution and usage by the campus. The
secondary portion of the central power plant was typically referred to as the central
chilled water plant and was comprised of three centrifugal chillers. In keeping with the
concept of fuel diversity, the chilled water plant was a true hybrid plant. The chilled
water plant was powered by a combination of electricity purchased from the utility
company, electricity produced by the cogeneration plant, and steam generated from the
primary level plant. However, for simplicity, the flow diagrams indicate only electricity
coming from the utility company and only steam from the boilers. The chilled water
plant was first brought on line in April 2006.

The primary chiller, manufactured by York, was of the centrifugal type and had a
refrigeration capacity of 2,400 tons. The driver of the chiller was a steam turbine fed by
the cogeneration unit and boilers as required. There were two other chillers rated at
1,000 tons each. They were also of the centrifugal type but were driven by electric
motors controlled by variable speed drives. To maximize the economic benefit of the
cogeneration plant, the steam-driven chiller was always called upon first whenever
campus chilled water requirements dictated that mechanical cooling was necessary. During periods when campus chilled water requirements exceeded the capacity of the steam chiller, the electric chillers were brought on line as necessary for supplemental purposes. There were times when chilled water requirements were marginal and outdoor conditions were favorable, particularly during the fall and spring seasons. During these conditions, water-to-water economizing heat exchangers were utilized to permit free cooling for energy conservation. Throughout the year, the chilled water plant was expected to work in unison with the cogeneration unit and boilers such that the overall economics were maximized through optimal selections of fuel and equipment operation.

3.6 Available Utilities

Available Utilities refers to those utilities delivered to the buildings either from the plant, directly from utility companies, or some combination of both. The available utilities were electricity, steam, chilled water, and natural gas.

In the case of electricity, the vast majority of buildings on campus were fed from the central heat and power plant through an underground electrical distribution system operating at 4,160 volts. This distribution system was sourced by a combination of the cogeneration unit and purchased electric utilities. Buildings not on the electrical distribution system were fed directly by the local electric utility company. Triad, Edgewood Park, Mansion Park, and the Team House are included in this group.
Only a minority of buildings on campus were fed from the chilled water plant through an underground distribution system. The chilled water plant addition was completed in April 2006. This measure marked the first phase of a lengthy project to centralize campus air conditioning. To minimize disruption to the campus, chilled water distribution piping was routed in conjunction with a steam pipe replacement project involving shared trenches. This approach necessitated coordination with prioritized steam line replacements and building chiller failures such that chilled water delivery to buildings would be phased-in over time. During FY07, the central chilled water plant fed the following buildings: Education Hall, Robinson, ESBY Gym, Campbell Library, and portions of the Student Center. The remaining buildings utilized stand-alone building water chillers fed by steam from the central heat and power plant, direct expansion air conditioning, or had no air conditioning at all.

The vast majority of buildings were fed with steam generated by the central heat and power plant. Steam was supplied through underground steam pipes at a pressure of 150 pounds per square inch and pipes that returned steam condensate to the plant. Exceptions to this arrangement included Triad, Edgewood Park, Mansion Park, and the Team House, which were configured with stand-alone natural gas-fired boilers, furnaces, or electric resistance heating.

Natural Gas, as an available utility, was fed to select buildings directly from the local natural gas utility, South Jersey Gas. This included Triad, Edgewood Park, and the Team House. These buildings utilized either dedicated stand-alone boilers or furnaces.
Also there were several gas-fired emergency electric power generators at select buildings. Due to the limited use of this equipment and resulting negligible fuel consumption, these units were omitted from this study.

3.7 Campus Energy Usage

Each available utility had one or more intended uses on campus. This section briefly describes these uses.

As discussed previously, electricity was supplied through utility purchases and/or generated on site at the central heat and power plant. However, the source of electricity did not affect how it was used on campus. In general, campus electricity was utilized for power, lighting, vertical transportation, and heating, ventilation and air conditioning (HVAC) systems. Power included wall, floor, power pole, or outdoor electric receptacles, laboratory power, and any other general power utility source available to building occupants. Lighting included both indoor and outdoor applications. HVAC systems included a vast multitude of equipment including electric chillers, direct expansion air conditioning units, window air conditioners, hot water and chilled water pumps, fans including those used in air handlers, supply, return, makeup, and exhaust. HVAC systems also included automatic temperature control systems and air compressor stations required to operate them.
Chilled water served only air conditioning systems on campus. Whether chilled water was produced at the central heat and power plant and distributed to buildings, or circulated in a building in conjunction with a dedicated chiller in the process of being phased out as an available utility, chilled water was solely dedicated to air conditioning systems.

Steam was widely used on campus in four general applications including heating, air conditioning, hot water, and laboratory processes. Through steam-to-water heat exchangers, steam from the central heat and power plant heated cold water, which was circulated through baseboard radiator heating, in-floor radiant heating, through coils in air handlers, or ductwork to provide comfort heating. Steam was also used as a heat source for several stand-alone absorption chillers utilized for air conditioning. The same was true for the central heating and power plant in that a portion of the steam was diverted to the steam-driven chiller. Steam was also widely used as a thermal source to heat cold water for domestic uses. Similar to comfort heating mentioned above, steam-to-water heat exchangers were utilized to raise the temperature of incoming cold water to a level adequate for domestic uses. Finally, there were a few laboratories on campus where steam served experimental equipment. However, steam usage by laboratory equipment contributed little to overall campus steam demand.

Natural gas serving a few outlying buildings/complexes was provided directly from a local gas company, South Jersey Gas. This included Triad, Team House, and Edgewood Park. For comfort heating, equipment in these buildings employed direct-
fired boilers or furnaces. For generation of domestic hot water, direct-fired boilers were used in conjunction with hot water circulation systems at these locations.

3.8 Energy Stream Reference Indices

For purposes of analysis and discussion, a system of notation has been devised for this study. Refer to Figure 3.3 below throughout the description that follows. All energy streams associated with this study have been assigned a two-digit number for reference.

Starting with the Primary Level utilities, each raw source that comprised electricity purchased from Atlantic City Electric, was numbered 01 through 09. Sources 01 through 04 were considered non-renewable utilities while sources 05 through 09 were considered renewable. Source 10 represents sourcing of wind-generated electricity, commonly referred to as w-recs from third-party renewable energy generator, Community Energy. These w-recs allow the offset of CO₂ produced during the generation of the standard grid mix of electricity, but involve no additional electricity being delivered from the grid. However, for the purpose of determining appropriate CO₂ emissions, the w-recs are treated as corresponding directly to purchasing wind-developed electricity. Fuel oil and natural gas utilities have been assigned as streams 11 and 12, respectively. Streams 13 through 17 represent individual utility feeds to equipment within the central heating and power plant and are discussed further below.
Within the primary plant level, stream 13 represents the sum of all raw sources bundled together into all electricity purchased by the university. Stream 14 is the natural gas feed to the cogeneration unit. Stream 15 is the fuel oil feed to boilers 1, 2, and 3. Stream 16 is the natural gas feed to boilers 1, 2, and 3. Stream 17 represents a “plant pass-through” natural gas stream directly serving those buildings that employ direct-fired heating and domestic hot water equipment. Streams 18 and 19 are steam condensate return flows back to the cogeneration and boilers.

At the Secondary Plant Level, several energy streams make up the complex interface between primary and secondary plant equipment. Similar to stream 17, stream 20 represents a “plant pass-through” electricity stream directly serving the available utility electricity to the campus. Stream 21 represents that portion of purchased electricity feeding the chilled water plant. Stream 22 refers to the electricity generated by the cogeneration unit feeding the available electricity to the campus. Stream 23 represents that portion of cogeneration plant electricity produced electricity that feeds the chilled water plant. Stream 24 refers to the steam produced by the cogeneration plant feeding the available steam to the campus. Note that steam produced by the cogeneration plant also serves the chilled water plant. For purposes of energy and CO₂ emissions accounting and balancing, steam and electricity used by the chilled water plant are considered to reflect the campus average that considers all sources of steam and electricity used by the campus. Stream 25 represents the return of all steam condensate from the campus to the plant. Stream 26 refers to that portion of the steam produced by the boilers that serves the chilled water plant. Stream 27 is the balance of the steam
produced by the boilers serving the available utility steam to the campus. Stream 28 is a sole chilled water output from the chilled water plant. Stream 29 represents the warmed chilled water that is returned to the chilled water plant for re-chilling since it is a closed-loop system similar to steam.

Moving to the Available Utilities level, Stream 30 is the sum of streams 20 and 22 and represents all electricity used by the campus for power, lighting, HVAC, etc. Stream 31 represents all chilled water that is distributed around campus and delivered to those buildings connected for the sole purpose of air conditioning. Similar to stream 31, stream 32 represents all steam that is distributed around campus and delivered to those buildings connected for purposes of heating, domestic hot water production, and laboratory processes. Stream 33 represents all natural gas directly serving those buildings that employ stand-alone heating and domestic hot water equipment.
3.9 Purchased Electricity Streams

This section describes and breaks down the components that make up electricity purchased by Rowan. Refer to Figure 3.4 below for detailed descriptions of these components.

In FY2007, Rowan University was supplied with transmission and distribution electrical service from the utility Atlantic City Electric (ACE). According to federal rules
and regulations, ACE and other load serving entities are required to issue a statement that describe all energy sources and their respective percentages that make up the resource blend of electricity they supply. The environmental label for July 1, 2006 through June 30, 2007 was obtained from ACE\textsuperscript{15} and the results are indicated in Figure 4 below.

Percentages for each energy source type are displayed in color code format to distinguish between renewable from non-renewable energy sources. During FY07, nearly 95\% of the electricity supplied by ACE came from non-renewable energy sources. However 43.9\% of this energy was generated from nuclear sources, which are considered to emit zero CO\textsubscript{2} plant emissions. ACE’s renewable portfolio accounted for the remaining 5.5\% balance of the entire resource blend.

To increase the percentage of renewable energy it purchased, Rowan University purchased w-recs. This energy was purchased from a third-party renewable generator, Community Energy. By purchasing 25\% energy from wind sources, Rowan University had rebalanced the resource blend to levels that favor CO\textsubscript{2} emissions-free technologies.
3.9.1 Energy Distribution, Quantification, and Analysis

Referring to Figure 3.5 below, all major energy streams for all levels have been identified and quantified on an annualized basis for FY07. For brevity, several of the energy values in Figure 3.5 are positioned inside of the process blocks. In all cases, the value inside of the block represents the energy input to that block. Sources for these data include copies of plant operator’s logs, utility bills, and energy accounting calculations.
Beginning with the primary level, each raw utility resource has an energy value associated with it. These energy values were determined by their relative proportion as defined in Atlantic City Electric’s Environmental Label. The non-renewable portion of ACE’s blend accounts for nearly 95% of the entire portfolio. Coal and nuclear energy account for the approximately 86% of the electric power purchased by Rowan University from ACE. Energy values are also posted for the renewable portion of ACE’s electric service and these values are broken down similarly in Figure 3.5.

In addition to purchasing electricity from ACE, Rowan University purchased wind-generated renewable energy certificates (w-recs) in a separate transaction.
Renewable energy certificates are tradable, non-tangible energy commodities in the United States that represent environmental attributes of the power produced from renewable energy sources and are sold separately from commodity electricity\textsuperscript{16}. One rec is equivalent to one megawatt-hour of electricity, which displaces carbon-emitting energy. The environmental attributes of recs can be used to offset the carbon footprint associated with other polluting activities. As a result, purchasing recs is a popular method of reducing greenhouse gas emissions for businesses and governmental organizations. During FY07, Rowan University purchased a total of 38,684,195 kWh from the grid, as well as 10,433,000 kilowatt-hours of w-recs. The electricity purchased from the grid actually came from a portfolio of sources that was representative of the ACE blend. However, for the purpose of accounting for carbon, it was assumed that 10,433,000 kWh were directly obtained from windpower, and the remaining 28,251,195 was reflected the ACE blend. The implications of this are discussed further in Riddell et al.\textsuperscript{19}

Values for fuel oil and natural gas for use in the central heat thermal and power plant are indicated under primary level as well. Natural gas is fed to the boilers as well as the cogeneration unit. Fuel oil is also fed to both plants. However, during FY07 no oil was consumed by the cogeneration plant due to an ongoing faulty liquid fuel pump system problem. All of the 47,811 gallons of fuel oil were consumed in the boilers only. The cogeneration plant consumed 60,383,999 cubic feet of natural gas during FY07. The boilers consumed 293,888,283 cubic feet of gas in FY07. Natural gas not used by the
cogeneration or heat plants accounted for 15,419,618 cubic feet in FY07 and typically
served apartments, e.g., Edgewood Park, using gas direct-fired hot water and heat.

Purchased electricity was split into two streams: 37,910,511 kilowatt-hours
(Stream 20) serving the campus as electric available utility, and 773,684 kilowatt-hours
serving the chilled water plant (Stream 21). The cogeneration unit produced electricity
and steam. In FY07, the cogeneration unit produced 3,284,400 kilowatt-hours while
serving the campus, reducing grid purchases. The cogeneration unit produced
21,037,000 pounds of steam for heating, cooling, hot water, and laboratory equipment on
campus.

To supplement thermal requirements, the boilers produced 258,704,586 pounds of
steam in FY07. 33,875,000 pounds of steam were utilized by the chilled water plant
while 224,829,586 pounds were distributed to the campus. Note that in general, the
chilled water plant utilized relatively small percentages of electricity and steam utilized
by the entire campus. This is because FY07 started in the middle of the first season the
chilled water plant was placed online, April 2006. At that time, only three buildings on
campus were connected to the plant so electricity use, associated with chilled water
production, was low.

As available utilities for multiple campus uses, the four campus consumer energy
sources are discussed below. Electricity consumed by the campus in FY07 reached
41,194,911 kilowatt-hours. As Figure 3.5 indicates, this energy is the sum of purchased
plus produced electricity and serves power, lighting, and HVAC systems on campus, minus the electricity used by the chilled water plant. The chilled water plant produced 2,020,263 ton-hours of cooling dedicated to air conditioning in FY07 from a combination of electric and thermal sources also shown in Figure 3.5. Steam consumed by the campus reached 245,866,586 pounds and was fed from the cogeneration unit and boilers in FY07. This thermal energy was used for heating, air conditioning, domestic hot water, and laboratory process applications. Finally, 15,419,618 cubic feet of natural gas was supplied throughout campus for non-central heating and power plant applications mostly comprising apartment complexes employing direct fired heating and hot water equipment.

3.9.2 CO₂ Emissions Distribution and Quantification

Figure 3.6 depicts quantities of CO₂ emissions in a manner similar to which Figure 3.5 conveys energy information. All values displayed in Figure 3.6 are in pounds of CO₂. All calculations were based on equations and coefficients appearing in the references found at the end of this thesis.¹⁷

Starting with the primary level, at 24,266,365 pounds of CO₂, in FY07, coal was by far the most significant contributor to CO₂ emissions within the ACE portfolio. Contributions from oil and gas were 161,880 pounds and 2,040,866 pounds of CO₂ respectively. Note that nuclear, while the largest provider of electricity from ACE, yields zero emissions and this fact greatly helped to balance ACE’s blend regarding CO₂ emissions.
emissions. All renewable energy sources from ACE and other utility companies yield zero CO₂ emissions. This includes captured methane gas. The release of methane gas directly to the atmosphere would result in greater CO₂ emissions than combustion of methane gas.

CO₂ emissions from the combustion of fuel oil for use in the boilers amounted to 1,029,849 pounds, while natural gas contributed 44,362,788 pounds for boilers and the cogeneration unit. All electric purchased in FY07 resulted in the effect of producing 26,469,111 pounds of CO₂. A relatively small portion (529,382 pounds of CO₂) of the electric purchased fed the chilled water plant. The balance (25,939,728 pounds of CO₂) was diverted to electric as an available campus utility. The cogeneration unit with its mix of fossil fuel inputs contributed 7,246,080 pounds of CO₂ in FY07. 2,824,584 pounds of CO₂ were associated with the electrical output of the plant. The remaining 4,421,496 pounds of CO₂ went toward the available steam campus utility.

The boilers contributed 36,296,203 pounds of CO₂ with a mixture of natural gas and fuel oil, with natural gas as fuel the majority of the time. 4,183,706 pounds of CO₂ was associated with usage by the chilled water plant. The remaining 32,112,497 pounds of CO₂ represented the steam used as an available campus utility. The hybrid steam/electric chilled water plant contributed 4,713,088 pounds of CO₂ in FY07 as a result of the blend of steam and electric inputs.
As available utilities for multiple campus usages, the four campus consumer energy sources are discussed below with regard to CO₂ emissions. Electricity, as an available utility, contributed 28,764,312 pounds of CO₂ and represented a blend of purchased and produced energy used for power, lighting, and HVAC systems on campus. The production of chilled water, used exclusively for air conditioning, contributed 4,713,088 pounds of CO₂. The production, distribution, and usage of steam accounted for the emission of 36,533,993 pounds of CO₂ in FY07. Natural gas used for heating and hot water in stand-alone apartment complexes contributed 1,850,354 pounds of CO₂ in FY07.

Figure 3.6 – Quantification of CO₂ Emissions throughout the campus energy delivery system cycle.
3.9.3 CO₂ Quantities per Unit of Host Energy

To assess the impact of CO₂ emissions of the campus energy delivery system at Rowan University, it is necessary to establish a system of ratios. In a system of ratios, one could readily navigate complex energy systems and work with individual systems and components to gain insight and come up with ways to reduce specific CO₂ emissions.

Figure 3.7 displays such ratios for all energy streams defined in this chapter. CO₂ emissions levels were divided by the associated energy quantities at every point. This also will enable future comparisons with similar systems.

Using government published CO₂ – Fuel ratios¹, as shown in Figure 3.7, Coal emits 2.47 pounds of CO₂ per pound consumed. Again, nuclear energy is considered to emit zero CO₂ emissions. Fuel oil emits 21.54 pounds of CO₂ per gallon. Natural Gas emits 0.12 pounds of CO₂ per cubic foot. The remaining sources from ACE are renewable and emit zero CO₂ emissions. As shown, the same ratios are used for the direct natural gas and oil purchases for the boilers and cogeneration unit.

All of these ratios carry over into the primary plant level, totalized and/or combined, to show the blended ratios that result at the plant machinery level. The generation of the electricity purchased emitted 0.684 pounds of CO₂ per kWh. This value includes wind renewable energy certificate purchases. The contribution of the cogeneration unit was 0.12 pounds CO₂ per cubic foot of natural gas. Note the resemblance the cogeneration unit has to
natural gas. This is due to the equipment running solely on natural gas during FY07.

Similarly, energy inputs to the boilers contributed 0.12 pounds of CO₂ per cubic foot of natural gas and 21.54 pounds CO₂ per gallon of fuel oil. An accounting of CO₂ for each point and stream is shown in Figure 3.7. Electricity and steam energy inputs to the chilled water plant account for 0.684 pounds CO₂ per kWh and 0.1235 pounds CO₂ per pound of steam. Now that all streams have been quantified and accounted for, one can review the CO₂ / energy ratios resulting from the blending that occurred as energy was diverted through the plant and campus.

<table>
<thead>
<tr>
<th>CO₂ Quantities per Unit of Energy</th>
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<tr>
<td>Primary Level</td>
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</table>

Figure 3.7 – CO₂ Emissions Quantities per Unit of Host Energy.
We now extend the above analysis and recalculate CO₂ emissions coefficients for steam and electricity produced by the cogeneration unit based on fractioning of the total energy produced by the cogeneration unit. Referring to Table 3.1 below, during FY2007, 60,383,999 cubic feet of natural gas were consumed by the cogeneration unit. No fuel oil was consumed by the cogeneration unit. Multiplying the consumed natural gas by the CO₂ emissions coefficient of 0.1200 pounds of CO₂ per cubic foot of natural gas resulted in 7,246,080 pounds of CO₂ emissions on the input side of the cogeneration plant. On the output side of the cogeneration unit, 3,284,400 kilowatts of electricity were produced and 21,037,000 pounds of steam were produced. To combine the two output energy quantities, standard energy conversion factors were used. Multiplying 3,284,400 kilowatts of electricity by 3,412.142 BTUs per kilowatt hour, we find 11,206,839,185 BTUs of output energy was produced in electricity alone. In a similar manner, multiplying 21,037,000 pounds of steam by 1,196.230 BTUs per pound of steam, we find 25,165,090,510 BTUs of output energy was produced in steam alone. Combining the two output energies, we find a total of 36,371,929,695 BTUs were produced by the cogeneration unit in FY07.

A preliminary CO₂ emissions coefficient for steam was then calculated by first assuming the electricity produced by the cogeneration unit was the same as the grid, 0.9810 pounds of CO₂ emissions per kilowatt hour. Multiplying 3,284,400 kilowatts of electricity by 0.9810 pounds of CO₂ emissions per kilowatt hour, we find a preliminary value of 3,221,996 pounds of CO₂ emissions, associated with electricity produced by the cogeneration unit. To balance CO₂ emissions on the input and output sides of the
cogeneration unit, accounting must take into consideration that emissions on both sides are equal. To calculate CO₂ emissions associated with steam, we must subtract 3,221,996 pounds of CO₂ emissions from 7,246,080 pounds of CO₂ emissions, attributing 4,024,083 pounds of CO₂ emissions to steam. To calculate a preliminary steam CO₂ emissions coefficient, we divide 4,024,083 pounds of CO₂ emissions by the amount of steam produced by the cogeneration unit, or 21,037,000 pounds. This calculation yields a result of 0.1913 pounds of CO₂ emissions per pound of steam as a preliminary CO₂ emissions coefficient for steam produced by the cogeneration unit. We will refer to the above extended analysis as Method 1.

A second approach (Method 2) used to determine the CO₂ emissions coefficient for steam produced by the cogeneration unit was to consider the fraction of total CO₂ emissions was attributed based on the energy ratio of steam energy over total energy. Recalling that 25,165,090,510 BTUs of steam output energy was produced out of a total of 36,371,929,695 BTUs produced by the cogeneration unit, through division, we find a fraction value of 0.69188. Multiplying this fraction by the total output CO₂ emissions of 7,246,080 pounds, we find that 5,013,434 pounds of CO₂ emissions were attributed to steam produced by the cogeneration unit in FY07. Through division of CO₂ emissions attributed to steam by the amount of steam produced, or 21,037,000 pounds, we find the final CO₂ emissions coefficient for steam produced by the cogeneration unit as 0.23832 pounds of CO₂ emissions per pound of steam produced by the cogeneration unit. Using a similar approach for electricity produced by the cogeneration unit, we find a final CO₂ emissions coefficient for electricity of 0.67977.
Table 3.1 – Determination of CO$_2$ emissions coefficients for steam and electricity produced by cogeneration unit

<table>
<thead>
<tr>
<th>FY 2006/2007 Cogeneration Unit Input Energy</th>
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<tbody>
<tr>
<td>Fuel</td>
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</tr>
<tr>
<td>Oil</td>
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<tr>
<td>Natural Gas</td>
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<tr>
<td>Total</td>
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<th>FY 2006/2007 Cogeneration Unit Output Energy</th>
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<tr>
<td>Energy Produced</td>
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<tr>
<td>Electricity</td>
</tr>
<tr>
<td>Steam</td>
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<tr>
<td>Total</td>
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<td>-----------------</td>
</tr>
<tr>
<td>Electricity</td>
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<tr>
<td>Steam</td>
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<tr>
<td>Total</td>
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<table>
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<tr>
<th>Energy Produced</th>
<th>Amount of Energy Produced in kWh of Electricity or Pounds of Steam</th>
<th>Final CO2 Emissions Coefficients</th>
<th>Total CO$_2$ Emissions in Pounds</th>
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<tbody>
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<tr>
<td>Steam</td>
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<td>0.23832</td>
<td>5,013,434</td>
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<tr>
<td>Total</td>
<td></td>
<td></td>
<td>7,246,080</td>
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</tbody>
</table>
The above analysis was extended further in the determination of CO$_2$ emissions coefficients for the four primary utilities distributed to the campus. Calculations of the CO$_2$ emissions coefficients followed a similar format as the calculations for steam and electricity produced by the cogeneration unit. Referring to Table 3.2 below, final CO$_2$ emissions coefficients are summarized at the bottom of the table. In summary, for every kilowatt-hour of electricity consumed by the campus for purposes of power, lighting, and HVAC, 0.7371 pounds of CO$_2$ were emitted. For every cubic foot of natural gas consumed by the campus for the purpose of direct-fired heating and hot water, 0.120593 pounds of CO$_2$ were emitted$^{19}$. Similarly, for every pound of steam consumed by the campus for the purpose of heating, domestic water, HVAC systems, and processes, 0.14503 pounds of CO$_2$ were emitted. For every ton-hour of chilled water consumed by the campus for purposes of air conditioning, 2.7141 pounds of CO$_2$ were emitted.
Table 3.2 -- Determination of CO$_2$ emissions coefficients for steam and electricity utilized by campus

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<tr>
<th>Fuel</th>
<th>Amount of Energy Consumed</th>
<th>Pounds of CO$_2$ Emissions Per Energy Unit</th>
<th>Total CO$_2$ Emissions, Pounds of CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Grid Electricity, kWh</td>
<td>38,684,195</td>
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<tr>
<td>Wind Rec Electricity, kWh</td>
<td>10,433,000</td>
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<tr>
<td>Grid Adjusted for Wind Recs, kWh</td>
<td>28,251,195</td>
<td>0.981</td>
<td>27,714,422</td>
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<tr>
<td>Natural Gas, Cubic Feet</td>
<td>369,689,900</td>
<td>0.120593</td>
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<tr>
<td>Oil, Gallons</td>
<td>47,811</td>
<td>22.384</td>
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<tr>
<td>Total Adjusted Grid, Natural Gas, &amp; Oil</td>
<td>73,366,638</td>
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FY 2006/2007 Plant Output Energy

<table>
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<tr>
<th>Utility Available to Campus</th>
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<th>Energy Conversion Coefficient in BTUs per Energy Unit</th>
<th>Total Energy in BTUs</th>
</tr>
</thead>
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<tr>
<td>Electricity, kWh</td>
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<td>3,412.142</td>
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<tr>
<td>Natural Gas, Cubic Feet</td>
<td>15,419,618</td>
<td>1,027</td>
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<td>Steam, Pounds</td>
<td>245,866,586</td>
<td>1,196.230</td>
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<tr>
<td>Chilled Water, Ton-hours</td>
<td>2,020,263</td>
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FY 2006/2007 Preliminary CO$_2$ Emissions Coefficients

<table>
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<th>Utility Available to Campus</th>
<th>Amount of Available Utility</th>
<th>Pounds of CO$_2$ Emissions Per Energy Unit</th>
<th>Total CO$_2$ Emissions, Pounds of CO$_2$</th>
</tr>
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<tbody>
<tr>
<td>Electricity, kWh</td>
<td>41,194,911</td>
<td>0.69825</td>
<td>28,764,347</td>
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<td>Natural Gas, Cubic Feet</td>
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<td>0.120593</td>
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<td>Steam, Pounds</td>
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<td>Chilled Water, Ton-hours</td>
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FY 2006/2007 Final CO$_2$ Emissions Coefficients

<table>
<thead>
<tr>
<th>Utility Available to Campus</th>
<th>Amount of Available Utility</th>
<th>Pounds of CO$_2$ Emissions Per Energy Unit</th>
<th>Total CO$_2$ Emissions, Pounds of CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, kWh</td>
<td>41,194,911</td>
<td>0.7371</td>
<td>30,366,128</td>
</tr>
<tr>
<td>Natural Gas, Cubic Feet</td>
<td>15,419,618</td>
<td>0.120593</td>
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<tr>
<td>Steam, Pounds</td>
<td>245,866,586</td>
<td>0.14503</td>
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<td>Chilled Water, Ton-hours</td>
<td>2,020,263</td>
<td>2.7141</td>
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<tr>
<td>Total</td>
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</table>
In FY07, electricity costs were $5,092,378 with 18,245,668 pounds of associated CO₂ emissions. Steam costs were $3,395,481 with 48,899,967 pounds of associated CO₂ emissions. Reflecting the period of FY07, the information assembled in this analysis can be utilized as baseline data for comparison in future related studies.

3.9.3 Campus Infrastructure Changes – Circa 2009

Between FY07 and 2009, significant changes to the campus infrastructure took place, while this study continued. The single 1.5 MW cogeneration unit was replaced with a plant that incorporated two cogeneration units totaling 4.7 MW of electrical output capacity. The new cogeneration plant is described in detail later in this paper, providing the main topic for analysis and discussion in this thesis. In addition, in early 2009, a new substation was brought online, reducing the number of high tension electric (primary) utility services from three to one and enabling Rowan University to purchase electricity directly from a single transmission line. By consolidating the primary electric utility services, Rowan University assumed a better position for future elimination of costly lower tension electric (secondary) utility services by connecting them into the campus electrical distribution system. The new substation transforms electricity at voltages from 69 kilovolts to 12.47 kilovolts. The substation is rated for a maximum capacity of 20 megavolt-amperes. Electricity at 12.47 kilovolts is distributed to campus buildings, some of which are in the process of being converted from an aged 4.16 kilovolt electrical distribution system that is being phased out. By owning, operating, and maintaining the 69/12.47 kilovolt substation and all other distribution equipment, Rowan University
avoids payment of distribution charges to their local electricity provider, Atlantic City Electric, and purchases transmission-level electricity directly from the grid. Therefore, grid electricity is currently limited to 20 megavolt-amperes, the rating of Rowan University’s substation. In addition, consolidation of the primary utility service from three to one provided a more streamlined approach in the monitoring of campuswide electrical demand via interval data. A discussion of interval data will follow in the next chapter of this thesis. The connection of electrical loads, associated with adding buildings to the campus electrical distribution system, increased the amount of campus electric demand on the new lightly-loaded substation.
Chapter 4
Period of Study and Campus Energy Systems, Production, and Usage

In this chapter, we discuss the sources of data utilized in this thesis. In addition, the time period studied for this thesis is primarily based is discussed. Further, an updated description of campus energy equipment and an analysis of on-campus energy production and energy usage are presented for the new study period.

4.1 Period of Study

As a reliable provider of electrical and thermal energy to the campus, the cogeneration plant is expected to operate year-round, 24 hours a day. However, turbine maintenance requirements involve approximately one week of downtime per year. A dual unit arrangement provides a means to shut down one unit at a time for maintenance, thereby permitting continued supply of electrical and thermal energy to the campus.

Utility infrastructure changes made between 2005 and 2009 resulted in a period of transition in which purchased and produced energy varied significantly. In the early part of year 2009, the cogeneration plant was in a period of equipment commissioning and regulatory environmental compliance testing. During the summer of 2009, commissioning and testing was completed and final air permitting was approved by the New Jersey Department of Environmental Protection. On September 1, 2009, plant operators began logging data for cogeneration units 1 and 2 separately, providing a starting point for tracking the performance of each unit. Given the timing of permit, the runtime of each cogeneration turbine, and availability of complete cogeneration plant
operational data, the period September 1, 2009 through August 31, 2010 was selected to establish the utility demand to study optimization of the cogeneration plant. This period provided data for the first year of significant runtime for both cogeneration turbines and followed commissioning and complete monitoring. In addition, this period encompassed academic year 2009 - 2010 and five summer sessions that took place in the summer season of 2010.

4.2 Sources of Data

Plant steam and electricity production data, and grid purchase data from Atlantic City Electric were gathered and reviewed. Daily totals for plant steam and electricity production for the boilers and cogeneration units was made available in a spreadsheet format, an excerpt of which is shown in Table 4.1. In addition, quarter-hour and hourly grid purchase data was made available in interval format through Energy Profiler Online, an online data download service provided by Atlantic City Electric. An excerpt of interval data is shown below in Table 4.2. To merge the hourly grid purchase data with the daily plant data, plant data was converted into hourly format by dividing daily values by 24, posting equal hourly values across each day, and adding the values with corresponding hourly interval data.
Table 4.1   Excerpt of Plant Steam and Electricity Production Data for September 2009

<table>
<thead>
<tr>
<th>SEPT 2009</th>
<th>BLR1 ST M</th>
<th>HRS</th>
<th>BLR2 ST M</th>
<th>HRS</th>
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</tbody>
</table>
4.3 Campus Energy Systems

Figure 4.1 is a schematic of a cogeneration system consisting of a combustion turbine, heat recovery steam generator, gearbox, and a generator. Air enters the inlet portion of the compressor section of the combustion turbine. Configured as a conical shape, the volume of the inlet portion of the compressor section is large relative to the outlet section of the compressor. Propelled by turbine blades attached to a rotating shaft, air is compressed as it moves along the compressor section to regions of reduced volume. At maximum compression, the air exits the compressor section and enters the combustion chamber where fuel is introduced and mixed with the compressed air at ratios that support combustion aided by a spark igniter. The fuel-air mixture is ignited, resulting in
elevated pressure of the combusted mixture (exhaust gases). Under high pressure, the exhaust gases exit the combustion chamber and enter the expansion section of the combustion turbine. In the expansion section, exhaust gases exert forces onto turbine blades resulting in rotation of the shaft. The expansion section is conical in shape, but is inverted, relative to the compressor section. This configuration maximizes the work done on the turbine blades by the exhaust gases by providing increased turbine blade area as gases pass through the expansion section. Exhaust gases exiting the expansion section enter a heat recovery steam generator where heat is transferred to water. The heat recovery steam generator (HSRG) is a plate frame heat exchanger where a mixture of water and cooled steam condensate returning from the campus, flows through tubes surrounded by a flow of exhaust gases. As the water/condensate mixture is heated by the exhaust gases, steam is produced for campus use. The combustion turbine shaft is coupled to a gearbox to reduce the shaft speed to levels suitable for use with a generator. Rated for speeds of 15,000 to 22,300 revolutions per minute, the combustion turbine requires a gearbox, to reduce shaft speed to 1,800 revolutions per minute, for three-phase electric power generation. The gearbox is coupled to the generator, where mechanical power is converted to electric power, to be distributed for campus use.

The Rowan University cogeneration system combustion turbines operate at constant volumetric flow rates. However, the combustion turbines operate at varied efficiencies as a function of inlet air conditions. Turbine inlet air flow is limited to fixed volumetric rates regardless of ambient air conditions. As ambient air temperature is increased, there is a corresponding reduction in air density. With a constant volumetric
flow rate, mass flow rate is reduced when temperature is increased. Therefore, for a given mass flow rate, turbine output is reduced as air temperature increases. Turbine efficiency is reduced as air temperature is increased since compression of warmer air requires more power.

Figure 4.1: Schematic of Typical Cogeneration Unit at Rowan University

Cogeneration Unit 1 has been rated a nominal electrical output of 1,210 kilowatts by its manufacturer, Solar Turbines, Inc. During the study period, Rowan University plant operators logged 130 days of 24-hour operation using natural gas as a fuel. Daily electrical outputs ranging from 20,215 to 32,567 kilowatt-hours were recorded during this period. By dividing the minimum and maximum consumption daily values by 24 hours, the average electrical power output for these days range from 842 to 1,357 kilowatts. For purposes of this study, Cogeneration Unit 1 has been assigned an upper limit electrical capacity of 1,357 kilowatts.
The manufacturer also published a thermal output range of 14,000 to 15,000
BTUs per kilowatt-hour for Cogeneration Unit 1. The manufacturer of the HRSG,
Rentech Boiler Systems, Inc., published a nameplate rating of 8,300 pounds of steam per
hour. During the study period, with natural gas as a fuel, 209,370 pounds of steam were
produced on the peak day of production for the year. By dividing the peak steam
production day value by 24 hours, we can approximate the peak thermal output range as
8,724 pounds of steam per hour. For purposes of this study, the upper limit of thermal
capacity of 8,724 pounds of steam per hour will be utilized for Cogeneration Unit 1.

Similarly, Cogeneration Unit 2 has been rated a nominal electrical output of 3,515
kilowatts by Solar Turbines, Inc. During the study period, Rowan University plant
operators logged 250 days of 24-hour operation using natural gas as a fuel. An electrical
output ranging from 65,782 to 92,814 kilowatt-hours of daily production was recorded
during this period. This results in an average electrical output range from 2,741 to 3,867
kilowatts. For purposes of this study, Cogeneration Unit 2 has been assigned an upper
limit electrical capacity of 3,867 kilowatts.

The manufacturer also published a thermal output range between 12,000 and
14,500 BTUs per kilowatt-hour. Rentech Boiler Systems, Inc., published a nameplate
rating of 19,550 pounds of steam per hour for the HRSG associated with Cogeneration
Unit 2. During the study period, with natural gas as a fuel, 486,240 pounds of steam
were produced on the peak day of production for the year. By dividing the peak steam
production day value by 24 hours, we can approximate the peak thermal output range as 20,260 pounds of steam per hour. For purposes of this study, the upper limit of thermal capacity of 20,260 pounds of steam per hour will be utilized for Cogeneration Unit 2.

Referring to Figure 4.2, Boiler 1 has been rated a nominal thermal output of 26,000 pounds of steam per hour by its manufacturer, Superior Combustion Industries, Inc. Original to the plant, Boiler 1 does not incorporate a stack gas economizer to preheat boiler feedwater, as with Boilers 2 and 3. Plant operators indicated that Boilers 1, 2, and 3 are operated as required to supplement the campus steam demand not met by the cogeneration units. Data recorded during the study period are indicative of a wide range of production values, including periods when the boilers were consistently operated at less than 50 percent of their capacities. For purposes of this study, the manufacturer-specified upper limits of thermal capacity of 26,000 pounds of steam per hour for Boiler 1 and 40,000 pounds of steam per hour, for Boilers 2 and 3 will be utilized. A summary of capacities for the cogeneration units and boilers can be found in Table 4.3 below.
4.4 Campus Energy Consumption and Demand

Grid purchase data was downloaded to a spreadsheet. The hourly data was totaled to provide grid purchases on a daily basis in a format similar to the plant steam and electricity production data. Daily produced electricity and purchased electricity was
combined to determine campus daily electrical consumption. In a similar fashion, steam data for the three boilers and two cogeneration units were combined on a spreadsheet to determine campus daily steam consumption.

Figure 4.3 is a plot of chronological campus electric demand in kilowatts for every hour of the study period. Note that this plot incorporates hourly grid interval data merged with daily cogeneration data that has been distributed on an hourly basis. As shown, peak demand values approached an order-of-magnitude of 10,000 kilowatts. Conversely, a low demand value of 302 kilowatts was recorded. The average electric demand was 5,762 kilowatts.

![Figure 4.3 -- Campus Electric Demand, kW versus hour September 1, 2009 through August 31, 2010](image)

Figure 4.4 is an electric load duration curve with the same hourly data shown in Figure 4.3. An electric load duration curve is generated by rearranging all interval data such that demand values are in the order from highest to lowest. This type of plot illustrates the relationship between generating capacity requirements and capacity
utilization. Load duration curves can assist in determining load dispatching, system planning, and reliability assessment. The area under the load duration curve represents the total electrical energy demanded by the system in kilowatt-hours.

Figure 4.4 -- Campus Electric Load Duration Curve September 1, 2009 through August 31, 2010

Figure 4.5 is a plot of campus steam demand in pounds for every hour of the study period. The peak steam demand value was 53,439 pounds per hour. Conversely, a low demand value of 4,788 pounds was recorded by plant operators. The average steam demand was 36,943 pounds per hour.
Figure 4.5 -- Campus Steam Demand, pounds of steam per hour versus hour September 1, 2009 through August 31, 2010

Figure 4.6 is a steam load duration curve with the same hourly data shown in Figure 4.5. Similar to an electric load duration curve, a steam load duration curve is generated by rearranging all interval data such that demand values are in the order from highest to lowest. Again, this type of plot illustrates the relationship between generating capacity requirements and capacity utilization. The area under the load duration curve represents the total heat energy demanded by the system in Steam pound-hours.
Tables 4.4 through 4.7 below show results of analyses for determination of CO₂ emissions coefficients for steam and electricity utilized by campus during the study period, September 1, 2009 through August 31, 2010. The results were determined the same way as described in Chapter 3 for FY07 data. The results of the analysis for FY07 data are repeated in Tables 4.4 through 4.7 for comparison.


<table>
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<tr>
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<tbody>
<tr>
<td>Grid Electricity, kWh</td>
<td>38,684,195</td>
<td>37,949,195</td>
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<tr>
<td>Wind Rec Electricity, kWh</td>
<td>10,433,000</td>
<td>14,705,000</td>
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<tr>
<td>Grid Adjusted for w-recs, kWh</td>
<td>28,251,195</td>
<td>27,714,422</td>
</tr>
<tr>
<td>Natural Gas, Cubic Feet</td>
<td>369,689,900</td>
<td>44,582,014</td>
</tr>
<tr>
<td>Oil, Gallons</td>
<td>47,811</td>
<td>76,509</td>
</tr>
<tr>
<td>Total</td>
<td>73,366,638</td>
<td>79,255,179</td>
</tr>
</tbody>
</table>
Table 4.5 – Conversions of Plant Output Energies into Common Energy Units for Comparison of FY2006/2007 and AY2009/2010.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount of Available Utility</td>
<td>Energy Conversion Coefficient in BTUs per Energy Unit</td>
</tr>
<tr>
<td>Electricity, kWh</td>
<td>41,194,911</td>
<td>3,412.142</td>
</tr>
<tr>
<td>Natural Gas, Cubic Feet</td>
<td>15,419,618</td>
<td>1.027</td>
</tr>
<tr>
<td>Steam, Pounds</td>
<td>245,866,586</td>
<td>1,196.230</td>
</tr>
<tr>
<td>Chilled Water, Ton-hours</td>
<td>2,020,263</td>
<td>12,000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, kWh</td>
<td>41,194,911</td>
<td>0.69825</td>
</tr>
<tr>
<td>Natural Gas, Cubic Feet</td>
<td>15,419,618</td>
<td>0.120593</td>
</tr>
<tr>
<td>Steam, Pounds</td>
<td>245,866,586</td>
<td>0.1547</td>
</tr>
<tr>
<td>Chilled Water, Ton-hours</td>
<td>2,020,263</td>
<td>2.3330</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, kWh</td>
<td>41,194,911</td>
<td>0.73713</td>
</tr>
<tr>
<td>Natural Gas, Cubic Feet</td>
<td>15,419,618</td>
<td>0.120593</td>
</tr>
<tr>
<td>Steam, Pounds</td>
<td>245,866,586</td>
<td>0.14503</td>
</tr>
<tr>
<td>Chilled Water, Ton-hours</td>
<td>2,020,263</td>
<td>2.7141</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5
Optimization Approach and Analysis

This chapter presents an overall approach and analyses for optimization of campus energy system operation. Insight into demands placed on energy systems is presented in this chapter. Energy demands must be related to campus activities. Energy usage patterns evolve. As a result, a system establishing groups of days to simplify datasets has been devised. A concept of characterization of modeled energy days will be developed and presented. Parameters established for optimization analysis will be discussed in this chapter. Finally, an algorithm developed for optimization will be presented.

5.1 Developing Characteristic Days

To consider optimization of the cogeneration plant, it is necessary to establish an understanding of the energy demands placed on the plant. Energy demands on the plant are primarily functions of seasonal weather activities, as well as, campus activities. As such, characterization of energy demand through a full year of seasonal weather changes and a full range of campus activities must be developed. This chapter presents a model that characterizes energy demand over a one-year period. The purpose of this chapter is to illustrate the development of this characterization and provide a model for potential use in future studies.
During the period September 1, 2009 through August 31, 2010 (the study period), utility infrastructure and campus square footage remained constant. This consistency permitted a look at the newly developed energy relationship between the cogeneration plant and campus. As the cogeneration plant was placed into priority operation, energy production and usage profiles emerged. It was necessary to develop a model that characterized campus energy demand through a full year of seasonal weather changes and a full range of campus activities to consider optimization of the new plant.

Plant steam and electricity production data, and grid purchase data from Atlantic City Electric were gathered and reviewed. Quarter-hour interval data from Atlantic City Electric was totalized to provide grid purchases on a daily basis in a format similar to the plant steam and electricity production data. Daily produced electricity and purchased electricity was combined to determine campus daily electrical consumption. In a similar fashion, steam data for the three boilers and two cogeneration units were combined on a single spreadsheet to determine campus daily steam consumption. Table 5.1 is an excerpt of a table that shows campus steam and electrical demand for the first and last five days of the study period.
Table 5.1 -- Excerpt of table showing campus steam and electrical consumption for first and last five days of study period.

<table>
<thead>
<tr>
<th>Day #</th>
<th>Date</th>
<th>Steam, Pounds</th>
<th>Electricity, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tuesday, September 01, 2009</td>
<td>745,000</td>
<td>198,229</td>
</tr>
<tr>
<td>2</td>
<td>Wednesday, September 02, 2009</td>
<td>882,000</td>
<td>198,858</td>
</tr>
<tr>
<td>3</td>
<td>Thursday, September 03, 2009</td>
<td>836,000</td>
<td>193,993</td>
</tr>
<tr>
<td>4</td>
<td>Friday, September 04, 2009</td>
<td>885,000</td>
<td>190,124</td>
</tr>
<tr>
<td>5</td>
<td>Saturday, September 05, 2009</td>
<td>913,000</td>
<td>196,542</td>
</tr>
</tbody>
</table>

...  

| 361   | Friday, August 27, 2010   | 997,440       | 29,844          |
| 362   | Saturday, August 28, 2010 | 954,646       | 30,095          |
| 363   | Sunday, August 29, 2010   | 1,029,554     | 28,957          |
| 364   | Monday, August 30, 2010   | 1,253,171     | 29,728          |
| 365   | Tuesday, August 31, 2010  | 1,079,942     | 29,556          |

TOTAL CAMPUS LOAD 338,140,224 49,513,257

Review of the complete table referenced in Figure 5.1 indicated a diverse range of campus steam and electricity consumption throughout the study period. Review of the steam and electricity demand ranges was conducted to characterize the diversities.

Academic calendars, published by the university, were obtained and are attached to this thesis. The academic calendar provided all university holidays, semester beginning and end dates for fall, spring, and all five summer sessions, and finals weeks for the study period. Summer sessions consist of 3, 5, and 8 week semesters completed within a three-month period. To complete the five summer sessions in three months, it is necessary to overlap several of the sessions. Accordingly, campus occupancy varies during the summer season. In addition, information from Rowan University’s Human Resources website indicated that during the summer season, the university switches from a five-day work schedule to a four-day work schedule, based on a Monday through Thursday...
workweek. Given the complexity of the academic calendar, it was necessary to first
define blocks of representative days we will call academic characteristic days.

An academic characteristic day represents a group of days that are similar to each
other, with respect to types of activities on campus. For example, during the study
period, there were 76 fall semester weekdays observed in the academic calendar for the
study period. During the 76 fall semester weekdays, it was assumed that campus
occupancy was constant. This assumption permitted the 76 days to be grouped and
represented by an academic calendar day we will call a Fall Semester Weekday. Table
5.2 below is a listing of twelve academic characteristic days developed from review of
the academic calendar.

Table 5.2 -- Academic Characteristic Days
Fall Semester Weekday
Fall Semester Weekend Day
Spring Semester Weekday
Spring Semester Weekend Day
Summer Session Weekday
Summer Session Weekend Day
Non-Semester Weekday
Non-Semester Weekend Day
University Holiday – Single Day
University Holiday – Break
Spring Break
Residential Student Move-in Day

Each day of the study period was assigned one of the academic characteristic days
from Table 5.2. A new table, Table 5.3, was generated by adding steam and electricity
demand columns to Table 5.1. This permitted a review campus steam and electricity
consumption by academic characteristic day. Table 5.3 is an excerpt of a table that shows campus steam and electrical consumption with academic characteristic days for the first and last five days of the study period.

Table 5.3 -- Excerpt of table showing assigned academic characteristic days for first and last five days of study period.

<table>
<thead>
<tr>
<th>Date</th>
<th>Assigned Academic Characteristic Day</th>
<th>Total Load Steam, Pounds</th>
<th>Total Load Electricity, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuesday, September 01, 2009</td>
<td>Fall Semester Weekday</td>
<td>745,000</td>
<td>198,229</td>
</tr>
<tr>
<td>Wednesday, September 02, 2009</td>
<td>Fall Semester Weekday</td>
<td>882,000</td>
<td>198,858</td>
</tr>
<tr>
<td>Thursday, September 03, 2009</td>
<td>Fall Semester Weekday</td>
<td>836,000</td>
<td>193,993</td>
</tr>
<tr>
<td>Friday, September 04, 2009</td>
<td>Fall Semester Weekday</td>
<td>885,000</td>
<td>190,124</td>
</tr>
<tr>
<td>Saturday, September 05, 2009</td>
<td>Fall Semester Weekend Day</td>
<td>913,000</td>
<td>196,542</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Friday, August 27, 2010</td>
<td>Residential Student Move-in</td>
<td>997,440</td>
<td>29,844</td>
</tr>
<tr>
<td>Saturday, August 28, 2010</td>
<td>Residential Student Move-in</td>
<td>954,646</td>
<td>30,095</td>
</tr>
<tr>
<td>Sunday, August 29, 2010</td>
<td>Residential Student Move-in</td>
<td>1,029,554</td>
<td>28,957</td>
</tr>
<tr>
<td>Monday, August 30, 2010</td>
<td>Residential Student Move-in</td>
<td>1,253,171</td>
<td>29,728</td>
</tr>
<tr>
<td>Tuesday, August 31, 2010</td>
<td>Residential Student Move-in</td>
<td>1,079,942</td>
<td>29,556</td>
</tr>
</tbody>
</table>

| TOTAL CAMPUS LOAD            | 338,140,224                         | 49,513,257               |

A review of assigned academic characteristic days indicated instances when campus steam and electricity consumption continued to vary within diverse ranges. For example, university holidays occurred during all four seasons requiring various modes of campus heating, ventilation, and air conditioning (HVAC) equipment operation. To characterize campus steam and electricity demand throughout the study period in a more precise manner, it was necessary to incorporate the effect of seasonal weather changes as they related to operation of campus HVAC equipment. To incorporate seasonal weather changes, we now define a more developed representative day we will call an Energy Characteristic Day.
Similar to the concept of the academic characteristic day, an energy characteristic day represents a group of days that are similar to each other, with respect to campus energy usage, in addition to campus activities. For example, during the study period, there were nine single university holidays, not counting multiple day university holiday break periods. Of the nine single university holidays, three holidays occurred when air conditioning (cooling) equipment was operating. Four of the nine holidays occurred when heating equipment was operating. Further, two of the nine holidays occurred during the fall and spring seasons, when operations of campus heating and cooling systems were in states of transition. By assigning each single university holiday into one of three categories, cooling, heating, and mixed-mode, the nine holidays were grouped and represented by three distinct energy characteristic days. During each energy characteristic day, campus energy usage profiles were verified as comparable, with the assumption that campus occupancy was consistent. This permitted each academic characteristic day to be mapped into an energy characteristic day. Variations in energy consumption and campus activities resulted in the development of sixteen energy characteristic days. Note that fall, spring, and summer semester energy characteristic days were not associated with cooling, heating, or mixed modes. A review of steam and electricity usages on semester days indicated minimal variation, such that adding HVAC operating mode days was not merited. Table 5.4 below is a listing of the sixteen energy characteristic days developed as part of this study. The purpose of establishing these characteristic days was to establish a limited number of days with which to characterize the complete year of energy demands. This list represents a workable number of days.
However, it is likely that careful analysis could reduce the number of characteristic days required to model the year.

Table 5.4 – Table of Energy Characteristic Days

<table>
<thead>
<tr>
<th>Fall Semester Weekday</th>
<th>Fall Semester Weekend Day</th>
<th>Spring Semester Weekday</th>
<th>Spring Semester Weekend Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer Session/Four-Day Weekday</td>
<td>Summer Session/Four-Day Weekend Day</td>
<td>Non-Semester Weekday – Cooling Mode</td>
<td>Non-Semester Weekday – Heating Mode</td>
</tr>
<tr>
<td>Non-Semester Weekend Day – Cooling Mode</td>
<td>Non-Semester Weekend Day – Heating Mode</td>
<td>University Holiday – Cooling Mode</td>
<td>University Holiday – Heating Mode</td>
</tr>
<tr>
<td>University Holiday – Mixed Mode</td>
<td>Christmas/New Years Break Day</td>
<td>Low Occupancy / Moderate Cooling</td>
<td></td>
</tr>
</tbody>
</table>

Each day of the study period was assigned one of the energy characteristic days from Table 5.4 based on energy usage and campus activity. Steam and electricity demand for individual days, assigned to energy characteristic days, were summed and divided by the number of individual days, to calculate daily consumption totals for each energy characteristic day. The energy characteristic days were summed and compared to actual data from the plant. Table 5.5 summarizes campus steam and electrical consumption with energy characteristic days.
Table 5.5 -- Energy characteristic day model with campus steam and electrical consumption.

<table>
<thead>
<tr>
<th>Energy Characteristic Day</th>
<th># Days</th>
<th>Average Lbs Steam/day</th>
<th>Total Steam, lbs</th>
<th>Average kWh Elec/day</th>
<th>Total Electric, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christmas/New Years Break Day</td>
<td>10</td>
<td>1,103,660</td>
<td>11,036,600</td>
<td>153,226</td>
<td>1,532,262</td>
</tr>
<tr>
<td>Fall Semester Weekday</td>
<td>76</td>
<td>842,000</td>
<td>63,992,000</td>
<td>200,431</td>
<td>15,232,780</td>
</tr>
<tr>
<td>Fall Semester Weekend Day</td>
<td>28</td>
<td>748,390</td>
<td>20,954,920</td>
<td>118,224</td>
<td>3,310,269</td>
</tr>
<tr>
<td>Non-Semester Weekday - Cooling Mode</td>
<td>5</td>
<td>1,141,480</td>
<td>5,707,400</td>
<td>121,690</td>
<td>608,449</td>
</tr>
<tr>
<td>Non-Semester Weekday - Heating Mode</td>
<td>15</td>
<td>937,410</td>
<td>14,061,150</td>
<td>139,336</td>
<td>2,090,042</td>
</tr>
<tr>
<td>Non-Semester Weekend Day - Cooling Mode</td>
<td>3</td>
<td>954,646</td>
<td>2,863,938</td>
<td>97,679</td>
<td>293,037</td>
</tr>
<tr>
<td>Non-Semester Weekend Day - Heating Mode</td>
<td>5</td>
<td>1,030,970</td>
<td>5,154,850</td>
<td>178,677</td>
<td>893,386</td>
</tr>
<tr>
<td>Spring Break Day</td>
<td>4</td>
<td>730,618</td>
<td>2,922,472</td>
<td>97,467</td>
<td>389,870</td>
</tr>
<tr>
<td>Spring Semester Weekday</td>
<td>74</td>
<td>837,534</td>
<td>61,977,516</td>
<td>124,237</td>
<td>9,193,526</td>
</tr>
<tr>
<td>Spring Semester Weekend Day</td>
<td>28</td>
<td>821,030</td>
<td>21,988,840</td>
<td>92,075</td>
<td>2,578,103</td>
</tr>
<tr>
<td>Summer Session/Four-Day Weekday</td>
<td>35</td>
<td>1,188,980</td>
<td>41,614,300</td>
<td>126,855</td>
<td>4,439,940</td>
</tr>
<tr>
<td>Summer Session/Four-Day Weekend Day</td>
<td>27</td>
<td>1,028,642</td>
<td>27,773,334</td>
<td>108,066</td>
<td>2,917,788</td>
</tr>
<tr>
<td>University Holiday - Cooling Mode</td>
<td>3</td>
<td>1,001,582</td>
<td>3,004,746</td>
<td>113,193</td>
<td>339,580</td>
</tr>
<tr>
<td>University Holiday - Heating Mode</td>
<td>4</td>
<td>849,000</td>
<td>3,396,000</td>
<td>186,812</td>
<td>747,247</td>
</tr>
<tr>
<td>University Holiday - Mixed Mode</td>
<td>2</td>
<td>762,000</td>
<td>1,524,000</td>
<td>195,516</td>
<td>391,031</td>
</tr>
<tr>
<td>Low Occupancy / Moderate Cooling</td>
<td>46</td>
<td>1,068,873</td>
<td>49,168,158</td>
<td>99,042</td>
<td>4,555,947</td>
</tr>
<tr>
<td><strong>Averaged campus demand from char.days</strong></td>
<td>365</td>
<td><strong>338,140,224</strong></td>
<td></td>
<td><strong>49,513,257</strong></td>
<td></td>
</tr>
</tbody>
</table>

Referring to Table 5.5, each energy characteristic day defined was assigned a group of individual days that occurred during the study period. The number of days varied by energy characteristic day as shown in column two. The "Average Lbs. Steam/Day" column represents daily averages of steam derived by averaging individual days within each characteristic day group. The "Total Lbs. Steam" column represents multiplication of columns two and three, providing daily steam demands, associated with each energy characteristic day. In a similar fashion, The "Average kWh Elec/Day" column was multiplied by the "# Days" column to provide daily electricity consumptions, associated with each energy characteristic day. The last row of Table 5.5 provides a summation of the number of days modeled throughout the study as a check. In addition, summations of modeled campus steam and electricity usage throughout the study period are shown in the last row of the table. The above model estimates steam consumption.
during the study period as 323,820,717 pounds of steam. Similarly, the model estimates electricity consumption during the study period as 49,513,257 kilowatt hours.

To assess the accuracy of the energy characteristic day model, actual energy data for individual days assigned to energy characteristic days, was entered into the energy characteristic day model and calculations were made. Results are shown in Table 5.6 below.

Table 5.6 -- Simulation of characteristic day model with actual campus steam and electricity.

<table>
<thead>
<tr>
<th>Characteristic Day</th>
<th>Example</th>
<th># Days</th>
<th>Steam lbs/day</th>
<th>Steam lbs</th>
<th>Electric kWh/day</th>
<th>Total Electric kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christmas/New Years Break Day</td>
<td>12/28/09</td>
<td>10</td>
<td>1,103,660</td>
<td>11,036,600</td>
<td>153,226</td>
<td>1,532,262</td>
</tr>
<tr>
<td>Fall Semester Weekday</td>
<td>12/08/09</td>
<td>76</td>
<td>842,000</td>
<td>63,992,000</td>
<td>200,431</td>
<td>15,232,780</td>
</tr>
<tr>
<td>Fall Semester Weekend Day</td>
<td>10/10/09</td>
<td>28</td>
<td>748,390</td>
<td>20,954,920</td>
<td>118,224</td>
<td>3,310,269</td>
</tr>
<tr>
<td>Non-Semester Weekday - Cooling Mode</td>
<td>08/19/10</td>
<td>5</td>
<td>1,141,480</td>
<td>5,707,400</td>
<td>121,690</td>
<td>608,449</td>
</tr>
<tr>
<td>Non-Semester Weekday - Heating Mode</td>
<td>01/11/10</td>
<td>15</td>
<td>937,410</td>
<td>14,061,150</td>
<td>139,336</td>
<td>2,090,042</td>
</tr>
<tr>
<td>Non-Semester Weekend Day - Cooling Mode</td>
<td>08/28/10</td>
<td>3</td>
<td>954,646</td>
<td>2,863,938</td>
<td>97,679</td>
<td>293,037</td>
</tr>
<tr>
<td>Non-Semester Weekend Day - Heating Mode</td>
<td>01/09/10</td>
<td>5</td>
<td>1,030,970</td>
<td>5,154,850</td>
<td>178,677</td>
<td>893,386</td>
</tr>
<tr>
<td>Spring Break Day</td>
<td>03/17/10</td>
<td>4</td>
<td>730,618</td>
<td>2,922,472</td>
<td>97,467</td>
<td>389,870</td>
</tr>
<tr>
<td>Spring Semester Weekday</td>
<td>03/03/10</td>
<td>74</td>
<td>837,534</td>
<td>61,977,516</td>
<td>124,237</td>
<td>9,193,526</td>
</tr>
<tr>
<td>Spring Semester Weekend Day</td>
<td>03/13/10</td>
<td>28</td>
<td>821,030</td>
<td>22,988,840</td>
<td>92,075</td>
<td>2,578,103</td>
</tr>
<tr>
<td>Summer Session/Four-Day Weekday</td>
<td>07/06/10</td>
<td>35</td>
<td>1,188,980</td>
<td>41,614,300</td>
<td>126,855</td>
<td>4,439,940</td>
</tr>
<tr>
<td>Summer Session/Four-Day Weekend Day</td>
<td>07/10/10</td>
<td>27</td>
<td>1,028,642</td>
<td>27,773,334</td>
<td>108,066</td>
<td>2,917,788</td>
</tr>
<tr>
<td>University Holiday - Cooling Mode</td>
<td>05/31/10</td>
<td>3</td>
<td>1,001,582</td>
<td>3,004,746</td>
<td>113,193</td>
<td>339,580</td>
</tr>
<tr>
<td>University Holiday - Heating Mode</td>
<td>11/27/09</td>
<td>4</td>
<td>849,000</td>
<td>3,396,000</td>
<td>186,812</td>
<td>747,247</td>
</tr>
<tr>
<td>University Holiday - Mixed Mode</td>
<td>11/03/09</td>
<td>2</td>
<td>762,000</td>
<td>1,524,000</td>
<td>195,516</td>
<td>391,031</td>
</tr>
<tr>
<td>Low Occupancy / Moderate Cooling</td>
<td>08/08/10</td>
<td>46</td>
<td>1,068,873</td>
<td>49,168,158</td>
<td>99,042</td>
<td>4,555,947</td>
</tr>
<tr>
<td>Averaged campus demand from char.days</td>
<td>365</td>
<td></td>
<td>338,140,224</td>
<td>49,513,257</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modeled campus demand: Characteristic days</td>
<td>365</td>
<td></td>
<td>338,140,224</td>
<td>49,513,257</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual campus demand 9/1/09 - 8/31/10</td>
<td>323,820,717</td>
<td>50,383,290</td>
<td>14,319,507</td>
<td>870,033</td>
<td>2%</td>
<td></td>
</tr>
</tbody>
</table>

As shown, total modeled campus steam demand for the study period was 338,140,224 pounds of steam. Actual steam demand recorded by plant operators during the study period was 323,820,717 pounds of steam. This equates to a difference of 14,319,507 pounds or 4%. In a similar fashion, total modeled campus electricity demand...
for the study period was 49,513,257 kilowatt hours. Actual electricity demand recorded by Atlantic City Electric was 50,383,290 kilowatt hours. This equates to a difference of 870,033 kilowatt hours or 2%. Differences of 4% and 2% are within a reasonable degree of engineering certainty. In addition, electricity and steam load duration curves were similar to characteristic day plots. It can be concluded that the above energy characteristic day model has sufficient accuracy for utilization within the overall optimization study.

5.2 Establishing Parameters

To characterize the performance of the cogeneration units and boilers, parameters must be developed to allow operation of the system to be optimized. The purpose of this chapter is to develop the parameters needed for the system model. A series of coefficients that characterize performance of the cogeneration units and boilers over the study period are presented. The parameters required are capacities of equipment, output per unit of natural gas fuel, cost of operation, carbon dioxide emissions per unit of natural gas fuel, and electricity purchased from the grid.

5.2.1 Efficiencies of Units

Given that the cogeneration plant and boilers utilize fossil fuels for energy input, it is important to quantify how efficient natural resources are being utilized during the production of electrical and thermal energies for campus usage. In this sense, we define efficiency as a ratio of input energy to the plant, divided by output energy produced by
the plant and distributed to the campus. Review of plant records indicates that Boiler 1 utilized 16,345,804 cubic feet of natural gas during the study period. During this period when natural gas was selected as fuel, Boiler 1 produced 13,307,779 pounds of steam. This resulted in an energy input/out ratio of 1.228 cubic feet of natural gas per pound of steam. By inverting this ratio and representing it as a coefficient, it can be concluded that for every cubic foot of natural gas input, 0.814 pounds of steam are produced by Boiler 1. In a similar manner, coefficients for Boilers 2 and 3 were developed and are summarized in Table 5.7.

In the case of Cogeneration Units 1 and 2, quantities of steam and electricity energies, produced when natural gas was selected as fuel during the study period, were incorporated in the development of coefficients. Separate coefficients for steam and electricity were developed given the dual output nature of the cogeneration units. A summary of energy input/output coefficients for Boilers 1, 2, and 3 and Cogeneration Units 1 and 2 are presented in Table 5.7 below.

<table>
<thead>
<tr>
<th>Energy System</th>
<th>Natural Gas Consumed in cubic feet (CF)</th>
<th>Electricity Produced in kilowatt-hours (kWh)</th>
<th>Electricity Produced in kilowatt-hours per cubic foot of natural gas consumed (kWh/CF-gas)</th>
<th>Steam Produced in pounds (lbs.)</th>
<th>Steam Produced in pounds per cubic foot of natural gas consumed (lbs./CF-gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler 1</td>
<td>16,345,804</td>
<td>-</td>
<td>-</td>
<td>13,307,779</td>
<td>0.814</td>
</tr>
<tr>
<td>Boiler 2</td>
<td>106,659,761</td>
<td>-</td>
<td>-</td>
<td>89,204,002</td>
<td>0.836</td>
</tr>
<tr>
<td>Boiler 3</td>
<td>69,569,439</td>
<td>-</td>
<td>-</td>
<td>59,275,051</td>
<td>0.852</td>
</tr>
<tr>
<td>Cogeneration Unit 1</td>
<td>66,312,732</td>
<td>3,952,599</td>
<td>0.0596</td>
<td>28,090,048</td>
<td>0.424</td>
</tr>
<tr>
<td>Cogeneration Unit 2</td>
<td>292,010,553</td>
<td>20,402,425</td>
<td>0.0699</td>
<td>121,057,073</td>
<td>0.415</td>
</tr>
</tbody>
</table>
Cogeneration unit 1 utilized 66,312,732 cubic feet of natural gas during the study period when natural gas was selected as a fuel. During this period, the generator component of cogeneration unit 1 produced 3,952,599 kilowatt-hours of electricity. This resulted in an overall gas-to-electrical energy conversion ratio of 16.777 cubic feet of natural gas per kilowatt-hour of electricity. Expressing this ratio in terms of a unit of natural gas, for every cubic foot of natural gas input, 0.0596 kilowatt-hours of electricity were produced. Also during the study period, the HSRG component of Cogeneration unit 1 produced 28,090,048 pounds of steam. This resulted in an overall gas-to-thermal energy conversion ratio of 2.361 cubic feet of natural gas per pound of steam. Expressing this ratio in terms of a unit of natural gas, for every cubic foot of natural gas input, 0.424 pounds of steam were produced. We can represent the overall energy balance of Cogeneration Unit 1 with the following relationships:

\[
E_{cgi} = E_{cge} + E_{cgh} - \text{Losses}
\]

Where \(E_{cgi}\) = Natural Gas Input Fuel Consumed, in cubic feet

\[
E_{cge} = \text{Electrical Output Energy Produced, in kilowatt-hours}
\]

\[
E_{cgh} = \text{Thermal Output Energy Produced, pounds of steam}
\]

1 cubic foot of natural gas \(\rightarrow\) 0.0596 kilowatt-hours + 0.424 pounds of steam

Cogeneration unit 2 utilized 292,010,553 cubic feet of natural gas during the study period when natural gas was selected as a fuel. During this period, the generator component of cogeneration unit 2 produced 20,402,425 kilowatt-hours of electricity. This resulted in an overall gas-to-electrical energy conversion ratio of 14.313 cubic feet
of natural gas per kilowatt-hour of electricity. Expressing this ratio in terms of a unit of natural gas, for every cubic foot of natural gas input, 0.0699 kilowatt-hours of electricity were produced. Also during the study period, the HSRG component of Cogeneration unit 2 produced 121,257,073 pounds of steam. This resulted in an overall gas-to-thermal energy conversion ratio of 2.408 cubic feet of natural gas per pound of steam. Expressing this ratio in terms of a unit of natural gas, for every cubic foot of natural gas input, 0.415 pounds of steam were produced. Similar to Cogeneration Unit 1, we can represent the overall energy balance with the following mathematical relationship for Cogeneration Unit 2:

\[
1 \text{ cubic foot of natural gas} \rightarrow 0.0699 \text{ kilowatt-hours} + 0.415 \text{ pounds of steam}
\]

A summary of energy input/output coefficients for Cogeneration Units 1 and 2 are presented in Table 5.7.

5.2.2 Cost and Emissions for Natural Gas and Electricity from the Grid

To characterize the economics associated with optimization of the cogeneration plant, parameters must be developed to allow economic performance to be optimized. In general, natural gas is purchased by Rowan University for a variety of commercial and residential applications including the cogeneration plant, boilers, heating and domestic water production equipment, emergency power generators, and laboratory equipment at various locations on campus. Each service is metered and designated by an account
issued by Rowan University’s local natural gas utility, South Jersey Gas, for billing and account management purposes. With a multitude of diverse natural gas services on campus, natural gas costs vary widely by location, gas volume, usage type, and rate structure. Consistent with the scope of this study, natural gas specifically purchased for the cogeneration units and boilers is presented solely in this paper.

The purchase cost of commercial natural gas for the cogeneration units and boilers at Rowan University can be broken down into three primary components, local transportation, regional transportation, and commodity. The local transportation component involves providing, maintaining, and operating equipment associated with local transportation and delivery of natural gas from a provider to the cogeneration units and boilers. Provided by South Jersey Gas, the local transportation component has defined utility rate structures known as utility rate tariffs. There are separate tariffs for the cogeneration units and boilers. The tariffs change over time and are regulated by the New Jersey Board of Public Utilities. According to the New Jersey State Department of the Treasury, natural gas sales and use tax exemptions are provided to cogenerating facilities in New Jersey. As such, Rowan University is exempt from paying sales tax on the natural gas commodity and both transportation components for natural gas serving the cogeneration units. However, Rowan University is not exempt from paying sales tax for natural gas serving the boilers, since boiler operations are not applicable under the cogeneration unit incentives.
The regional transportation component involves providing, maintaining, and operating equipment associated with the transportation of natural gas from wellheads through interstate pipelines for delivery to a provider. Unlike the local transportation component, the regional transportation component is not regulated. The regional transportation component is included with commodity billing. Again, Rowan University is exempt from paying sales tax for natural gas serving the cogeneration units, but not for the boilers.

The commodity purchasing component strictly involves the sale of natural gas on unregulated bases. Commodity rates are set on a daily basis through futures contracts established by trading futures on the New York Mercantile Exchange (NYMEX). Monthly volumes of natural gas are estimated and purchased in advance of actual usage months at rates established by the date of sale. When volumes of natural gas are purchased in excess of actual usage, remarketing of unused natural gas takes place on a monthly basis. During remarketing, it is not unusual to sell unused natural gas at a rate significantly less than commodity rates.

Rowan University utilizes a complex natural gas procurement strategy that involves hedging futures contracts in conjunction with decision-making by a committee referred to as the Energy Review Panel\textsuperscript{21}. Through frequent monitoring of online real time pricing, historical and current data are analyzed and lock-in rate and gas allocation models are developed for decision-making by the Energy Review Panel. The overarching goal in this process is to provide utility budgetary control in a deregulated
market. Rowan University also applies the same process to purchase electricity, a utility that is structured quite similar to natural gas.

Local transportation, regional transportation, and commodity natural gas is purchased by Rowan University in units of heat energy known as therms, which represents 100,000 BTU of energy. Therms are quantities of natural gas based on volumetric flow and adjusted for variations in the heat energy contents of the delivered natural gas. A conversion factor, known as a therm factor, varies and is reported on monthly natural gas bills. The therm factor converts volume (cubic feet) to thermal energy content (therms). Utility-owned natural gas meters are read by South Jersey Gas and measure gas volumes in cubic feet. Cogeneration and heat plant operators also monitor and record daily volumetric natural gas consumption in units of cubic feet separately, for cogeneration units 1 and 2, and boilers 1, 2, and 3. To conduct energy analyses, comparison of plant data with utility bill information requires an application of monthly therm factors to plant volumetric flow readings for consistency in units and accuracy in analysis.

Variations in heat energy content of delivered natural gas results in performance and efficiency variations in the cogeneration units and boilers. With less heat energy content in the fuel, additional natural gas volume is required to achieve the same output as fuel with higher content, resulting in additional purchases and increased costs. As discussed above, therm factors take the varying heat energy content of delivered natural gas into account.
Given the complexities of energy and economic analyses and efforts required to address multiple rate structures, futures contracts, tariffs, taxation, decision-making for purchases, remarketing, conversions, and energy content variation, it is beyond the scope of this research to conduct a high level energy and cost accounting review of all plant and utility bill records for the cogeneration units and boilers during the review period.

Further, purchasing strategies evolve over time in response to changes in regulatory, statutory, and market conditions. Given that this paper is intended to create a model for future studies, it is reasonable to incorporate historical energy cost data published by the United States Energy Information Administration (EIA). Further, the EIA publishes natural gas prices in terms of cubic feet which, is consistent with units utilized in Rowan University plant records.

The EIA provides historical monthly natural gas prices for a variety of United States consumers. Historical monthly natural gas prices for New Jersey commercial consumers, during months of the review period, September 2009 through August 2010, were researched and downloaded from the EIA website. It was confirmed through EIA representatives, that the published prices incorporated local transportation, regional transportation, and commodity pricing. The published prices varied on a seasonal basis. Natural gas prices for all 12 months of the study period were averaged to establish a single rate that could be applied throughout the study period for purposes of this paper. The average natural gas price was $9.5242 per thousand cubic feet, and was used as an
economic coefficient for natural gas in this paper. Seasonally varying values were within 7% of the economic coefficient.

Similarly, the EIA provides historical monthly electricity prices for a variety of United States consumers. Historical monthly electricity prices for New Jersey commercial consumers, during months of the review period, September 2009 through August 2010, were researched and downloaded from the EIA website. As with the case of natural gas, it was confirmed through EIA representatives that the published prices included local distribution, regional transmission, and generation pricing. Electricity prices for all 12 months of the study period were averaged to a single rate and applied throughout the study period for purposes of this paper. The average electricity price was $0.1372 per kilowatt-hour, which was used as the coefficient for electricity in this paper.

To quantify the environmental impact associated with optimization of the cogeneration plant, we must establish parameters that address environmental performance of the cogeneration plant. For purposes of this paper, environmental performance of the cogeneration plant is presented as a function of carbon dioxide (CO₂) emissions. CO₂ emissions, in the context of the cogeneration plant, come from two primary sources, grid electricity and natural gas.

Electricity purchased from Atlantic City Electric is produced by multiple generating plants that produce electricity in various ways. Resources utilized by the generating plants are categorized as renewable and non-renewable by ACE. In general,
renewable resources are considered to be free of CO\textsubscript{2} emissions, while non-renewal resources are associated with CO\textsubscript{2} emissions. On an annual basis, ACE publishes a listing of generating resources and their percentage contribution to the total electricity they provide. In addition, Rowan University purchases wind renewable energy certificates (w-recs), adding to the complexity of establishing a parameter for CO\textsubscript{2} associated with electricity purchased from the grid.

A high level analysis of CO\textsubscript{2} quantification for grid electricity purchased by Rowan University was incorporated in a paper, “Assessing carbon dioxide emissions from energy at a university,” published in 2008\textsuperscript{22}. This publication was based on Rowan University energy data from 2006 and 2007. A review of ACE’s mixture of generating resources and associated percentage contributions from 2007 through 2010 indicates that minimal changes had taken place. In addition, w-rec purchases were relatively constant during the same period. Therefore, it is reasonable to incorporate CO\textsubscript{2} emissions for grid electricity from the high level analysis presented in the 2008 paper into this analysis. A value of 0.981 pounds of CO\textsubscript{2} emitted per kilowatt-hour of electricity generated from the grid, is an appropriate coefficient for utilization in this paper.

In the case of natural gas utilized by the cogeneration plant, an analysis of CO\textsubscript{2} emissions was also presented in the 2008 paper mentioned in the paragraph above. The paper used a value of 120.593 pounds of CO\textsubscript{2} emitted per 1,000 cubic feet of natural gas as obtained from the EIA\textsuperscript{23}. A summary of economic and environmental coefficients for boilers 1, 2, and 3, and Cogeneration Units 1 and 2 are presented in Table 5.8 below.
5.2.3 Algorithm for Analysis

Optimized operation requires numerical analyses that process multiple instructions over wide ranges of data, subject to multiple boundary conditions. To develop programming instructions for the evaluation of operating data and equipment contributions, a generalized flowchart was prepared and is shown in Figure 5.1. As shown, two criteria groups establish program boundary conditions that are consistent with objectives of this study. Criteria groups include minimization of operational costs and minimization of carbon dioxide emissions. A comparator determines whether data meets the established criteria. Data that does not meet the program criteria ceases to be processed further, reaching the end point of the program. Data that meets program criteria is further processed with calculations and routed back through the program and compared with criteria again. The process continues to repeat until all feasible solutions are identified.

Table 5.8 -- Economic and Environmental Coefficients for Grid Electricity and Natural Gas Utilities

<table>
<thead>
<tr>
<th>Coefficient Description</th>
<th>Coefficient</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Electricity Cost</td>
<td>0.1372</td>
<td>$/kW-hr</td>
</tr>
<tr>
<td>Natural Gas Cost</td>
<td>9.5242</td>
<td>$/1000 ft³</td>
</tr>
<tr>
<td>Grid Electricity CO₂ Emissions</td>
<td>0.981</td>
<td>lb CO₂/kW-hr</td>
</tr>
<tr>
<td>Natural Gas CO₂ Emissions</td>
<td>120.593</td>
<td>lb CO₂/1000 ft³</td>
</tr>
</tbody>
</table>
To determine optimal operation of the cogeneration plant, parameters developed in Chapter 5 were combined with operational data and a set of repetitive instructions, to evaluate the data over wide ranges. Numerical programming was chosen in conjunction
with matrix linear algebra. Vectors were defined to characterize contributions of primary plant equipment in various operational configurations, over equipment operating ranges.

A general format for vector representation is as follows:

\[ V = [\text{CG1}, \text{CG2}, \text{BO1}, \text{BO2}, \text{BO3}, \text{GRI}] \]

Where,  
\begin{align*}
\text{CG1} &= \text{Cogeneration Unit 1 (1.2 MW unit)} \\
\text{CG2} &= \text{Cogeneration Unit 2 (3.5 MW unit)} \\
\text{BO1} &= \text{Boiler 1 (26,000 pounds/hour)} \\
\text{BO2} &= \text{Boiler 2 (40,000 pounds per hour)} \\
\text{BO3} &= \text{Boiler 3 (40,000 pounds per hour)} \\
\text{GRI} &= \text{Grid Purchases (KW)}
\end{align*}

The vectors defined below, were developed to numerically characterize plant equipment operation in various configurations as follows:

**Equipment Operation Vector, EQUIPOP**

EQUIPOP is an array that represents operational states of plant energy production equipment including electricity supplied from the grid. The array is represented as a vector that characterizes all permutations of the general vector format shown above, with respect to equipment operational states. To represent “ON” and “OFF” states of equipment operation, a numerical system of zeroes and ones is utilized. If a particular piece of equipment is in a shutdown state, this state is represented with a zero. Conversely, if the equipment is in an operating state, this state is represented with a one. For example, EQUIPOP = [0, 1, 0, 1, 0, 1] represents a state of equipment operation as follows:
Cogeneration Unit 1 is shut down, [0]
Cogeneration Unit 2 is operating at full capacity, [1]
Boiler 1 is shut down, [0]
Boiler 2 is operating at full capacity, [1]
Boiler 3 is shut down, [0]
Grid is supplying 1 kW of electrical energy, [1]

**Electrical Production Vector, ELECPROD**

ELECPROD is an array that represents electrical power in kilowatts solely produced by the various plants at capacity. \( \text{ELECPROD} = [1,200, 3,500, 0, 0, 0, 0] \) represents the following states of electrical energy production by the various aspects of the campus plant:

- Cogeneration Unit 1 produces 1,200 kilowatts of electrical power, \([1,200]\)
- Cogeneration Unit 2 produces 3,500 kilowatts of electrical power, \([3,500]\)
- Boiler 1 does not produce electrical power, \([0]\)
- Boiler 2 does not produce electrical power, \([0]\)
- Boiler 3 does not produce electrical power, \([0]\)
- Grid is not supplying electrical power, \([0]\)

**Steam Generation Vector, STEAMPROD:**

STEAMPROD is an array that represents steam produced by the cogeneration and boiler plants at capacity. Cogeneration units 1 and 2 are equipped with heat recovery steam generators, one each, to utilize turbine exhaust heat for conversion of water into steam. \( \text{STEAMPROD} = [8724, 20260, 26000, 40000, 40000, 0] \) represents the following states of thermal energy production by the campus energy system at full capacity:
Cogeneration Unit 1 produces 8,724 pounds of steam per hour at capacity,

Cogeneration Unit 2 produces 20,260 pounds of steam per hour at capacity,

Boiler 1 produces 26,000 pounds of steam per hour at capacity,

Boiler 2 produces 40,000 pounds of steam per hour at capacity,

Boiler 3 produces 40,000 pounds of steam per hour at capacity,

Grid does not supply steam,

**Natural Gas Usage Vector, GASUSE:**

GASUSE is an array that represents natural gas consumed by the cogeneration and boiler plants at capacity. The array is represented as a vector that characterizes all permutations of natural gas usage. Values in the array are expressed in units of 1,000 cubic feet of natural gas per hour (MCF/hour). GASUSE = [20.575, 48.819, 31.941, 47.847, 46.948, 0] represents the following states of natural gas consumed by the campus energy system at full capacity:

- Cogeneration Unit 1 consumes 20.575 MCF/hour of gas,
- Cogeneration Unit 2 consumes 48.819 MCF/hour of gas,
- Boiler 1 consumes 31.941 MCF/hour of natural gas,
- Boiler 2 consumes 47.847 MCF/hour of natural gas,
- Boiler 3 consumes 46.948 MCF/hour of natural gas,
- Grid does not consume natural gas,

**Grid Electricity Usage Vector, GRIDUSE:**

GRIDUSE is an array that represents electricity supplied by the grid. The array is represented as a vector that characterizes all permutations of electricity supplied by the
Values in the array are expressed in units of kilowatts. For example, GRIDUSE = [0, 0, 0, 0, 1] represents the following states of electricity supplied by the grid:

- Cogeneration Unit 1 supplies electricity to the campus only, [0]
- Cogeneration Unit 2 supplies electricity to the campus only, [0]
- Boiler 1 supplies steam to the campus only, [0]
- Boiler 2 supplies steam to the campus only, [0]
- Boiler 3 supplies steam to the campus only, [0]
- 1 kilowatt of electricity is being supplied by the grid, [1]

Development of the optimization algorithm incorporated the use of the vectors described above, a series of data files representing steam and electricity demand for each characteristic day, and a set of code programming instructions based on the objectives of this thesis. The program was run with MATLAB software with input files created by merging utility interval data with plant operating records. The complete code used for these analyses can be found in Appendix I.
Chapter 6

Optimized Operations

In this chapter, we discuss optimized operations of the cogeneration plants and boilers. This includes how optimization is defined within the context of this paper. A review of operating hours and utilization analysis of each cogeneration and boiler unit is presented. Equipment operating constraints are presented. Finally, a description of optimized operations, as defined by this paper, is presented.

In general, optimization goals for energy production and conversion facilities are driven by strategies developed by ownership and management. Historically, such goals and strategies have often been driven by maximizing revenues and minimizing expenses. This approach often takes the form of negotiating energy contracts to minimize utility costs, minimizing labor, minimizing production and conversion equipment downtime, minimizing waste, and maximizing plant equipment efficiency and output. This chapter focuses on optimizing the operation of cogeneration and boiler plant equipment based on the two goals set forth in this paper, economics of natural resources, and the environment.

Figure 6.1 is an electric load duration curve developed with data from the study period. Electrical capacity limit lines for utility and cogeneration plant equipment have been superimposed onto the load duration curve. The limit line for the utility (grid) is shown coincident with a campus peak demand that approached 10,000 kilowatts during the study period. This representation is intended to illustrate plant equipment electrical capacities, relative to campus demand. Typically, the grid represents an abundant supply
of electricity that is limited by the capacities of generation, transmission, and distribution equipment owned by local electricity providers.

Base load hours of operation for each cogeneration unit are shown in Figure 6.1 and indicated by vertical red lines that intersect with horizontal red capacity limit lines superimposed onto the load duration curve. Of a possible 8,760 hours of operation per year, there exists sufficient campus electrical demand to operate only cogeneration unit 1 for 8,300 hours. This represents approximately 95 percent or 346 days of the study period. In a similar manner, throughout the study period, there exists sufficient electrical demand to operate only cogeneration unit 2 for 6,061 hours. This represents approximately 69 percent or 253 days of the study period. Again, we show that the grid is available to provide electricity in excess of levels produced by the cogeneration units when operated individually, in combination, or in the case neither unit is operating. A discussion of combined operation of cogeneration units 1 and 2 follows this paragraph.
Figure 6.1 -- Campus electric load duration curve during study period with utility and cogeneration plant equipment capacity limit lines superimposed. Shown as peak campus electrical demand, actual grid capacity is 20 megavolt-amperes, limited by 69/12.47 kilovolt substation owned, operated, and maintained by Rowan University.

Figure 6.2 is a variation of Figure 6.1 with electrical capacity limit lines in a stacked configuration. As shown, cogeneration unit 1 is designated as the base load unit and first placed into operation to supply a base electrical load that exists for 95 percent of the study period. When campus electrical load reaches a level greater that 1.2 megawatts, cogeneration unit 2 is placed into operation. Combined operation of cogeneration units 1 and 2 provide a supply of electricity limited to 4.7 megawatts to an electrical load with a duration of 3,940 hours or 45 percent of the study period. Again, the grid is available to provide electricity in excess of levels produced by the cogeneration units, individually, in combination, or in the case neither unit is operating.
Figure 6.2 -- Campus electric load duration curve during study period with stacked utility and cogeneration plant equipment electrical capacity limit lines superimposed.

Figure 6.3 is a variation of Figure 6.2 with the order of cogeneration unit operation reversed. As shown, cogeneration unit 2 is designated as the base load unit and first placed into operation to supply a base electrical load that exists for 5,800 hours or 66 percent of the study period. When campus electrical load reaches a level greater that 3.5 megawatts, cogeneration unit 1 is placed into operation. Combined operation of cogeneration units 1 and 2 provide a supply of electricity to 4.7 megawatts to an electrical load with a duration of 3,940 hours or 45 percent of the study period. Again, the grid is available to provide electricity in excess of levels produced by the cogeneration units, individually, in combination, or in the case neither unit is operating. Plant records indicated that during the study period, cogeneration unit 1 operated 3,617 hours and cogeneration unit 2 operated 6,574 hours. These hours of operation are of an order of magnitude that is reasonable compared to the configuration presented in Figure 6.3. This
is indication that the Figure 6.3 represents the sequence of operation likely implemented
during the study period.

Figure 6.3 -- Campus electric load duration curve during study period with
stacked utility and cogeneration plant equipment electrical capacity limit lines
superimposed.

Figure 6.4 is a steam load duration curve developed with data from the study
period. Steam capacity limit lines for cogeneration plant and boiler equipment have been
superimposed onto the load duration curve. Again, base load hours of operation for each
cogeneration unit and boiler are indicated by vertical red lines that intersect with
horizontal red capacity limit lines and the load duration curve. By observation, neither
cogeneration units 1 or 2 alone have sufficient capacities to meet the required base
campus steam load. In combination, cogeneration units 1 and 2 can meet the required
base campus steam load. Also by observation, boiler 1 can meet the required base
campus steam load. Boilers 2 and 3 have individual capacities equivalent to 75% of the
peak steam demand of 53,439 pounds per hour reached during the study period. By
summation of steam capacities of the cogeneration units and boilers, the combined steam
capacity is 134,984 pounds of steam per hour. The combined steam capacity of the cogeneration units and boilers is greater than 2.5 times the peak steam demand reached during the study period. The purpose of this redundancy is to achieve equipment reliability. Unlike having the flexibility of purchasing electricity from by the grid, the cogeneration units and boilers are energy conversion devices. There is no district steam or other steam utility source in the vicinity of the Rowan University campus. This configuration of equipment with varying capacities provides multiple choices for flexible equipment operation, to meet diverse campus steam demand conditions in a reliable manner.

Figure 6.4 -- Campus steam load duration curve during study period with boiler and cogeneration plant equipment steam capacity limit lines superimposed. Steam is in units of pounds.

To meet campus steam demand requirements, the boilers can be started from cold or adjusted for increased output while already in hot standby mode. Recalling that the boilers at Rowan University are water-tube boilers, boiler feedwater flows through a series of tubes, the outside surfaces of which are heated by combustion gases that flow
around the tubes as the gases pass through the boilers. The tubes are manufactured from copper. Other metallic boiler components are manufactured from various grades of steel used for casings, drums, shells, tube sheets, inlet and outlet pipe connections, burner components, stack components, and fasteners. Material properties such as thermal conductivity and thermal expansion vary among dissimilar metallic materials. In an assembly comprised of dissimilar metals such as a boiler, care must be taken to avoid rapid temperature transitions as dissimilar metals will expand or contract at different rates. Uneven expansion and contraction of dissimilar results in stresses associated with components that interfere with each other. Such stresses can cause material failures such as cracking and leaks.

The flame temperature of combustion for a mixture of natural gas and air is 1950°C. Ambient room temperature within the boiler plant is an average 25°C. When the boilers have been shut down for an extended period, materials within the boilers are at room temperature. During boiler start-up, boiler materials, combustion chamber and stack components, and feedwater in tubes in the vicinity of the burner and flame are heated from 25°C to temperatures approaching 1950°C, a difference of 1925°C. The boiler shells are insulated from the combustion chamber with refractory materials and as a result, sustain reduced temperature differentials during boiler start-up. If the burner firing rate is set to minimum during a cold start-up, the distribution of heat to surfaces within the boiler will be gradual and controlled, allowing for reduced thermal stresses, resulting in a less incidence of material failures. Referred to as the warm-up phase of boiler start-up, operating the boiler at minimum firing rate is a period during which the
boiler cannot achieve consistent steam production at rated levels. Therefore, during warm-up, the boiler cannot be relied on to meet increased campus steam demand requirements.

Another factor in the warm-up phase of boiler start-up is phase change of the boiler feedwater. Boilers at Rowan University generate steam. Unlike their hot water boiler counterparts that increase boiler return water temperature only, steam boilers must convert feedwater into steam, in addition to increasing feedwater temperature. To change feedwater to steam, heat energy must be added to the feedwater at a rate equal to, or greater than, the latent heat of vaporization for water, 970.4 BTUs per pound. Increased heat energy requirements for conversion from water to steam result in longer boiler warm-up and start-up periods.

From cold starts, warm-up periods for the three boilers at Rowan University generally take two-to-three hours. After this period, the boilers can be placed online, operate in normal steam production mode, and respond to varying campus steam demand requirements.

Hot standby mode refers to maintaining heat in the boilers by continuous low-level firing, in conjunction with periodic increased firing for short durations. Operating boilers in hot standby mode requires fuel that does not directly contribute to steam production. However, this fuel penalty provides steam production readiness and reliability in response to varied campus steam demands. Boiler 1, the oldest of the three
boilers and built in 1960, requires continuous low-level firing and increased incremental firing once or twice on a manual basis each 8-hour shift to maintain hot standby mode. Boilers 2 and 3 were built in 2004 and are equipped with mud drum heaters. The mud drum heaters automatically maintain 75 pounds per square inch of steam pressure in the boiler tubes for warm standby mode. For hot standby mode, the mud drum heaters in boilers 2 and 3 increase pressure in the boiler tubes to 135 pounds per square inch once per 8-hour shift. Automated mud drum heater operation reduces standby fuel usage and cost penalties. Once in hot standby mode, boilers 1, 2, and 3 require 20-30 minutes to be placed online, operate in normal steam production mode, and respond to varying campus steam demand requirements. As a result of these operational considerations, the simulation assumes all boilers operate at least five percent capacity all the time.

The heat recovery steam generators (HRSGs) for cogeneration units 1 and 2 use no fuel and therefore are not considered fired. Rather, the HRSGs utilize combustion gases exhausted from the turbine components of cogeneration units 1 and 2. While the gas turbine generator sets can be brought online rapidly from a cold start, the HRSGs require warm up before they generate adequate steam. Similar to the boilers, HRSG feedwater flows through a series of tubes, the outside surfaces of which are heated by combustion gases that flow around the tubes as the gases pass through the HRSGs. HRSG materials of construction include copper and various grades of steel. With similarities in terms of materials of construction and methods of heat transfer, the HRSGs have similar problems as the boilers, requiring consideration for the rapidity at which they are brought on line.
Since there is no burner or fire to regulate, the HRSGs are unfired shell and tube heat exchangers that do not have formal warm-up controls like the boilers. Manufactured in 2006 and rated at 8,300 pounds per hour and 19,550 pounds per hour, the HRSGs are physically smaller and rated for considerably less steam output than the boilers. The HRSGs have smaller components that can better sustain rapid variations in thermal activity. From a cold start, the HRSGs can be placed online, operate in normal steam production mode, and respond to varying campus steam demand requirements within two hours. However, the electricity generation components of the cogeneration units can be brought on line faster. From a cold start, the turbogenerator components of the cogeneration units can be placed on line and operate in normal production mode within one hour.
Chapter 7

Results and Discussion

This chapter presents results and discussion of point-in-time and break-even analyses based on economic and environmental conditions, characteristic day simulations, and sensitivity analyses of the mathematical model developed in this thesis. One goal of this chapter is to provide an increased understanding of the relationships between input and output variables of the model. Relationships between operation of the cogeneration plant and variations of electricity purchased from the grid will be presented and discussed. Conditions will be identified that recommend alternate cogeneration unit operating scenarios based on costs and CO₂ emissions. The role of the cogeneration plant for reliability and emergency preparedness will be discussed.

7.1 Point in Time Analysis -- Economics

In review of cogeneration plant operational choices, we now take a look at economic considerations through point-in-time calculations. Let’s assume cogeneration unit 1 is operating at full capacity. Recall that at full capacity, cogeneration unit 1 produces 1,357 kilowatts of electricity and 8,724 pounds of steam per hour. Coefficients presented in Table 5.7 indicate that for every cubic foot of natural gas consumed by cogeneration unit 1, 0.0596 kilowatt-hours of electricity are produced. We calculate the one-hour natural gas consumptive requirement as follows:

\[
\frac{1,357 \text{ kWh}}{\text{hour}} \times \frac{1 \text{ CF Gas}}{0.0596 \text{ kWh}} = 22,768.46 \text{ CF Gas per hour}
\]
Recall from Table 5.8 that the cost of natural gas during the study period is $9.5242 per 1,000 cubic feet. We calculate the one-hour natural gas purchase cost for cogeneration unit 1 as follows:

\[
22,768.46 \frac{CF\ Gas}{hour} \times \frac{\$9.5242}{1,000\ CF\ Gas} = \$216.85\ per\ hour
\]

Replacing the energy production of cogeneration unit 1 requires that an amount of electricity and steam equivalent to the amount that would have been produced by cogeneration unit 1, be purchased from the grid, and produced by the campus boilers, respectively. Recall from Table 5.8 that the cost of electricity from the grid during the study period is $0.1372 per kilowatt hour. We calculate the cost of the electricity purchased from the grid as follows:

\[
1,357 \frac{kWh}{hour} \times \frac{\$0.1372}{kWh} = \$186.18\ per\ hour
\]

Boiler 2 was selected for operation due to its high efficiency rating relative to boiler 1. We first calculate how much natural gas is required for boiler 2 to produce 8,724 pounds of steam. From Table 5.7, boiler 2 produces 0.836 pounds of steam for every cubic foot of natural gas. We calculate how much natural gas is required for boiler 2 to produce 8,724 pounds of steam as follows:

\[
8,724 \frac{lbs\ Steam}{hour} \times \frac{1\ CF\ Gas}{lb\ Steam} = 10,435.40\ Cubic\ feet\ of\ gas\ per\ hour
\]
Adding the cost of purchasing electricity from the grid to the cost of purchasing natural gas to produce steam in boiler 2, we calculate the hourly cost of shutting down cogeneration unit 1 as follows:

\[
\frac{\$186.18 \text{ hour}}{\text{hour}} + \frac{\$99.39 \text{ hour}}{\text{hour}} = \$285.57 \text{ per hour}
\]

Recall the cost of operating cogeneration unit 1 at full capacity is $216.85 per hour. This amount is $68.72 per hour less expensive that purchasing electricity from the grid and operating boiler 2 to supplement the steam that would have been produced by cogeneration unit 1. From this calculation, it can be concluded that, under current cost and emissions, operating cogeneration unit 1 is more economical than purchasing electricity from the grid as long as there is sufficient demand for the electricity and steam produced by cogeneration unit 1.

By preparing similar calculations to cogeneration unit 2, we find the following:

\[
3,867 \frac{kWh}{\text{hour}} \times \frac{1 \text{ CF}}{0.0699 kWh} = 55,321.89 \text{ cubic feet of gas per hour}
\]
\[
55,321.89 \frac{CF \text{ Gas}}{\text{hour}} \times \frac{\$9.5242}{1,000 \text{ CF Gas}} = \$526.89 \text{ per hour}
\]
Adding the cost of purchasing electricity from the grid to the cost of purchasing natural gas to produce steam in boiler 2, we calculate the hourly cost of shutting down cogeneration unit 2 as follows:

\[
\frac{530.55}{\text{hour}} + \frac{230.81}{\text{hour}} = \frac{761.36}{\text{hour}}
\]

The cost of operating cogeneration unit 2 at full capacity is $526.89 per hour. This amount is $234.47 per hour less expensive that purchasing the equivalent amount of electricity from the grid and operating boiler 2 to supplement the steam that would have been produced by cogeneration unit 2. From this calculation, it can be concluded that operating cogeneration unit 2 is more economical than purchasing from the grid.

We now review economic operating scenarios representing simultaneous operation of both cogeneration units at full capacity. Recall that cogeneration units 1 and 2 have respective operating costs of $216.85 per hour and $526.89 per hour. By adding these values, we obtain a single value of $743.74 per hour for combined cogeneration
unit operation. In a similar manner, we combine grid and boiler hourly costs for the scenario involving shutdown of both cogeneration units. We sum the values $285.57 per hour (cogeneration unit 1 off) and $761.36 per hour (cogeneration unit 2 off) for a total value of $1,046.93 per hour representing a combined unit shutdown. Comparing hourly operating costs associated with simultaneous cogeneration operation and simultaneous shutdown resulted in a difference of $303.19 per hour. As in the cases of individual operation of cogeneration units 1 and 2 at full capacity, purchasing electricity from the grid and operating boiler 2 is more expensive than simultaneous operation of both cogeneration units at full capacity by $303.19 per hour. It can also be concluded that cogeneration units 1 and 2 operated in any combination is less expensive that purchasing electricity from the grid and producing steam from campus boilers, as long as there is sufficient demand for the electricity and steam produced.

7.2 Economic Break-Even Point

From the above, we observe that purchasing electricity from the grid and operating the boilers is more expensive than all possible combinations of cogeneration unit operation, as long as there is sufficient demand for both the electricity and steam produced by the cogeneration units. We now determine the economical break-even point between cogeneration unit operation and grid purchases. To determine the economical break-even point, we set the cost of electricity (in $/kWh) as the variable, and assume full cogeneration unit production. We then solve for the cost of electricity that makes the two
cases equivalent. The cost of running both cogeneration units, \( C_c \) for one hour is found by

\[
C_c = \left( 1,357 \text{ kWh} \times \frac{1 \text{ CF Gas}}{0.0596 \text{ kWh}} \times \frac{\$9.5242}{1,000 \text{ CF Gas}} \right) \\
+ \left( 3,867 \text{ kWh} \times \frac{1 \text{ CF Gas}}{0.0699 \text{ kWh}} \times \frac{\$9.5242}{1,000 \text{ CF Gas}} \right) = \$743.74
\]

Combined, the two cogeneration units produce 5,224 kWh and 28,984 lb steam per hour. The hourly cost of grid purchases and operating the boilers to replace production from both cogeneration units, \( C_{g+b} \) can be found by

\[
C_{g+b} = \left( 5,224 \text{ kWh} \times C_g \frac{\$}{\text{kWh}} \right) + \left( 28,984 \text{ lb Steam} \times \frac{1 \text{ CF Gas}}{0.836 \text{ lb Steam}} \times \frac{\$9.5242}{1,000 \text{ CF Gas}} \right) = 5,224 C_g \frac{\$-\text{kWh}}{\text{kWh}} + \$330.20
\]

Where \( C_g \) is the cost of purchasing electricity from the grid in \$/kWh.

Using parameters previously developed in this thesis: \$9.5242 per cubic foot for natural gas, 0.836 pounds of steam produced per cubic foot of natural gas consumed by boiler 2, 0.0596 kilowatt hours produced per cubic foot of natural gas consumed by cogeneration unit 1, and 0.0699 kilowatt hours produced per cubic foot of natural gas consumed by cogeneration unit 2.

At the economic break-even point, \( C_c = C_{g+b} \)
\[ 743.74 = 5224 C_g \frac{\$}{kWh} + 330.20 \]

Solving for \( C_g \), the economic break-even point for production versus purchasing is:

\[ C_g = \$0.07916 \text{ per kilowatt hour} \]

Applying the same methodology to individual operating cases of cogeneration units 1 and 2, below are the following economic break-even points for production versus purchasing.

\[ C_{Cogen1} = \$0.0866 \text{ per kilowatt hour} \]
\[ C_{Cogen2} = \$0.0766 \text{ per kilowatt hour} \]

Table 7.1 includes a summary of hourly costs for operating scenarios of the cogeneration units at full capacity. The economic break-even points developed above are also listed in Table 7.1.
Table 7.1 – Summary of CO₂ emissions, costs, and break-even points for operating scenarios of cogeneration units at full capacity.

<table>
<thead>
<tr>
<th>Operating Scenario</th>
<th>Operating Cost, $/hr</th>
<th>CO₂ Emissions, lbs/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operate Cogeneration Unit 1</td>
<td>216.85</td>
<td>2,745.72</td>
</tr>
<tr>
<td>Replace Cogen Unit 1 with Grid and Boilers</td>
<td>285.57</td>
<td>2,589.66</td>
</tr>
<tr>
<td>Operate Cogeneration Unit 2</td>
<td>526.89</td>
<td>6,671.43</td>
</tr>
<tr>
<td>Replace Cogen Unit 2 with Grid and Boilers</td>
<td>761.36</td>
<td>6,716.04</td>
</tr>
<tr>
<td>Operate Cogeneration Units 1 and 2</td>
<td>743.74</td>
<td>9,417.15</td>
</tr>
<tr>
<td>Replace Cogen Units 1 and 2 with Grid and Boilers</td>
<td>1046.93</td>
<td>9,305.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cogeneration Operating Break-even Points</th>
<th>Economic, $/kWh</th>
<th>Environmental, lb CO₂/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operate Cogeneration Unit 1</td>
<td>0.0866</td>
<td>1.096</td>
</tr>
<tr>
<td>Operate Cogeneration Unit 2</td>
<td>0.0766</td>
<td>0.9695</td>
</tr>
<tr>
<td>Operate Cogeneration Units 1 and 2</td>
<td>0.0792</td>
<td>1.0023</td>
</tr>
</tbody>
</table>

7.3 Point in Time Analysis – Environmental Impacts

We now quantify the environmental impacts of operating the cogeneration units in terms of CO₂ emissions. Again, we assume cogeneration unit 1 is operating at full capacity, which produces 1,357 kilowatts of electricity and 8,724 pounds of steam per hour. The one-hour natural gas consumptive requirement was determined to be 22,768.46 cubic feet of gas per hour above. From Table 5.8, the environmental coefficient for natural gas is 120.593 pounds of CO₂ per 1,000 cubic feet. We therefore calculate hourly CO₂ emissions associated with operating cogeneration unit 1 as follows:

\[
\frac{22,768.46 \text{ CF Gas}}{\text{hour}} \times \frac{120.593 \text{ lb CO}_2}{1,000 \text{ CF Gas}} = 2,745.72 \text{ pounds of CO}_2 \text{ per hour}
\]

Again, shutting down cogeneration unit 1 requires purchasing electricity from the grid and operating boiler 2 to supplement steam production. From Table 5.8, the environmental coefficient for grid electricity is 0.981 pound of CO₂ per kilowatt hour.
We calculate the hourly CO₂ emissions associated with purchasing electricity from the grid as follows:

\[
\frac{1,357 \text{ kWh}}{\text{hour}} \times \frac{0.981 \text{ lb CO₂}}{\text{kWh}} = 1,331.22 \text{ pounds of CO₂ per hour}
\]

It was determined above that operating boiler 2 to supplement steam produced by cogeneration unit 1 results in consumption of 10,435.40 CF gas per hour. Again using the environmental coefficient for natural gas, we calculate the hourly CO₂ emissions associated with operating boiler 2 instead of cogeneration unit 1 as follows:

\[
\frac{10,435.40 \text{ CF Gas}}{\text{hour}} \times \frac{120.593 \text{ lb CO₂}}{\text{1,000 CF Gas}} = 1,258.44 \text{ pounds of CO₂ per hour}
\]

Purchasing electricity from the grid and operating boiler 2 results in the following hourly CO₂ emissions:

\[
\frac{1,331.22 \text{ lb CO₂}}{\text{hour}} + \frac{1,258.44 \text{ lb CO₂}}{\text{hour}} = 2,589.66 \text{ pounds of CO₂ per hour}
\]

Recall that operating cogeneration unit 1 resulted in CO₂ emissions of 2,745.72 pounds of CO₂ per hour. This value is 156.06 pounds of CO₂ per hour greater than purchasing electricity from the grid and supplementing the steam with boiler 2. From the above, it can be concluded that purchasing electricity from the grid and operating boiler 2 is slightly cleaner than operating cogeneration unit 1 at full capacity. The percentage difference between the two scenarios is 5.7 percent.
By preparing similar calculations to cogeneration unit 2, we find the following:

\[
\frac{55,321.89 \text{ CF Gas}}{\text{hour}} \times \frac{120.593 \text{ lb CO}_2}{1,000 \text{ CF Gas}} = 6,671.43 \text{ pounds of CO}_2 \text{ per hour}
\]

\[
\frac{3,867 \text{ kWh}}{\text{hour}} \times \frac{0.981 \text{ lb CO}_2}{\text{kWh}} = 3,793.53 \text{ pounds of CO}_2 \text{ per hour}
\]

\[
\frac{24,234.45 \text{ CF Gas}}{\text{hour}} \times \frac{120.593 \text{ lb CO}_2}{1,000 \text{ CF Gas}} = 2,922.51 \text{ pounds of CO}_2 \text{ per hour}
\]

\[
\frac{3,793.53 \text{ lb CO}_2}{\text{hour}} + \frac{2,922.51 \text{ lb CO}_2}{\text{hour}} = 6,716.04 \text{ pounds of CO}_2 \text{ per hour}
\]

Operating cogeneration unit 2 results in CO2 emissions of 6,671.43 pounds of CO2 per hour. Shutting down cogeneration unit 2, purchasing electricity from the grid, and supplementing the steam with boiler 2, results in CO2 emissions of 6,716.04 pounds of CO2 per hour. This is a difference of 44.61 pounds of CO2 per hour and indicates that at full capacity, operating cogeneration unit 2 is slightly cleaner than purchasing electricity from the grid. The percentage difference between the two scenarios is 0.67%.

Given there are slight, yet mixed CO2 emission variations for individual cogeneration unit operation, we must look at operating scenarios representing simultaneous operation. Recall that cogeneration units 1 and 2 have respective hourly CO2 emissions values of 2,745.72 pounds of CO2 per hour and of 6,671.43 pounds of CO2 per hour. By adding these values, we obtain a single value of 9,417.15 pounds of CO2 per hour for combined cogeneration unit operation. In a similar manner, we combine grid and boiler emissions values for the scenario involving shutdown of both
cogeneration units. We add the values 2,589.66 pounds of CO₂ per hour (cogeneration unit 1 off) and 6,716.04 lb pounds of CO₂ per hour (cogeneration unit 2 off) for a total value of 9,305.70 pounds of CO₂ per hour representing a combined unit shutdown. Comparing CO₂ emissions associated with simultaneous cogeneration operation and simultaneous shutdown resulted in a difference of 111.45 pounds of CO₂ per hour. As in the case of individual operation of cogeneration unit 1 at full capacity, purchasing electricity from the grid and operating boiler 2 is slightly cleaner than operating both cogeneration units at full capacity. The percentage difference between the two scenarios is 1.2 percent.

7.4 Environmental Break-Even Point

We now determine the environmental break-even point between cogeneration unit operation and grid purchases. To determine the environmental break-even point, we set the grid emissions coefficient (in lb CO₂/kWh) as the variable, and assume full cogeneration unit production. It can be assumed that CO₂ emissions associated with the combustion of natural gas is unlikely to change. We then solve for the grid emissions coefficient that makes the two cases equivalent.

Let \( G_c \) = CO₂ emissions of operating both cogeneration units at full capacity for one hour.

Let \( G_{g+b} \) = CO₂ emissions of purchasing grid electricity and operating the boilers for one hour.
Let \( A \) = Hourly CO\(_2\) emissions of electricity purchased from the grid as a variable in pounds of CO\(_2\) per kilowatt hour.

We recall that the combined steam output of cogeneration units 1 and 2 is 28,984 pounds of steam per hour. The combined electrical output of cogeneration units 1 and 2 is 5,224 kilowatts. Recalling the following parameters previously developed in this thesis: 0.981 pounds of CO\(_2\) per kilowatt hour for electricity purchased from the grid, pounds of CO\(_2\) per 1,000 cubic foot for natural gas, 0.836 pounds of steam produced per cubic foot of natural gas consumed by boiler 2, 0.0596 kilowatt hours produced per cubic foot of natural gas consumed by cogeneration unit 1, and 0.0699 kilowatt hours produced per cubic foot of natural gas consumed by cogeneration unit 2. The CO\(_2\) emissions associated with operating both cogeneration units at full capacity for one hour is found by

\[
G_c = \left(1,357 \text{ kWh} \times \frac{1 \text{ CF Gas}}{0.0596 \text{ kWh}} \times \frac{120.593 \text{ lb CO}_2}{1,000 \text{ CF Gas}}\right) + \left(3,867 \text{ kWh} \times \frac{1 \text{ CF Gas}}{0.0699 \text{ kWh}} \times \frac{120.593 \text{ lb CO}_2}{1,000 \text{ CF Gas}}\right)
\]

\[= 9,417.15 \text{ pounds of CO}_2\]

The CO\(_2\) emissions associated with grid purchases and operating the boilers at full capacity for one hour is found by

\[
G_{g+b} = \left(5,224 \text{ kWh} \times \frac{A \text{ lb CO}_2}{\text{kWh}}\right) + \left(28,984 \text{ lb Steam} \times \frac{1 \text{ CF Gas}}{0.836 \text{ lb Steam}} \times \frac{120.593 \text{ lb CO}_2}{1,000 \text{ CF Gas}}\right)
\]

\[= \frac{5,224 A \text{ kWh}}{\text{lb CO}_2} + 4,180.94 \text{ lb CO}_2\]
However, $G_c = G_{g+b}$

$9,417.15 \text{ lb CO}_2 = \frac{5.224 \ A \text{kWh} \ lb \text{ CO}_2}{\text{kWh}} + 4,180.94 \ lb \text{ CO}_2$

Solving for A, the environmental break-even point for production versus purchasing is given by:

$A = 1.0023 \text{ pounds of CO}_2 \text{ per kilowatt hour}$

Applying the same methodology to individual operating cases of cogeneration units 1 and 2, below are the following economic break-even points for production versus purchasing.

$A_{\text{Cogen1}} = 1.0960 \text{ pounds of CO}_2 \text{ per kilowatt hour}$

$A_{\text{Cogen2}} = 0.9695 \text{ pounds of CO}_2 \text{ per kilowatt hour}$

Table 7.1 is a summary of hourly CO$_2$ emissions and costs for operating scenarios of the cogeneration units at full capacity. Economic and environmental break-even points developed above are also listed in Table 7.1.

Figure 7.1 is a decision matrix for operating the cogeneration plant under varying grid economic and environmental conditions. The y-axis represents the cost of grid electricity in dollars per kilowatt hour of grid electricity. The red horizontal line represents the economic break-even point of $0.07916/\text{kWh}$, developed above. Below
this break-even point are left and right quadrants that represent less expensive operational scenarios. The x-axis represents grid CO₂ emissions in pounds of CO₂ per kilowatt hour of grid electricity. The red vertical line represents the environmental break-even point of 1.0023 lb-CO₂/kWh, developed above. To the left of this break-even point are upper and lower quadrants that represent cleaner operational scenarios. The quadrants identify scenarios of operating the cogeneration unit versus operating the boilers and purchasing electricity from the grid. Each quadrant is labeled such that operating decisions can be made as grid electricity changes over time in both cost and CO₂ emissions. As a reference, current grid cost and CO₂ emissions conditions are denoted as a point in Figure 7.1.

Figure 7.1 – Decision matrix for cogeneration plant operation versus grid purchases and boiler operation as functions of grid electricity costs and emissions.

7.5 Simulations based on Characteristic Days

Tables 7.2 and 7.3 below contain optimized cost and CO₂ emission values for energy characteristic days. The values were generated through simulations by the
algorithm presented in this thesis. The algorithm processed input files that included actual plant data from example days that corresponded with the energy characteristic days shown.

The first simulation determined the most economical mode of cogeneration plant operation for each energy characteristic day. As shown in Table 7.2, energy characteristic days are listed along with their respective number of days they occurred during the study period. The number of days column is followed by two columns that indicate the number of hours per day each cogeneration unit should be operated to achieve optimal economic operation. As shown, cogeneration unit 2 operates 24 hours per day throughout the study period. Cogeneration unit 1 does not operate continuously throughout the study period to achieve optimal economic operation. This is due to varying campus electrical demand that, at times, is below the combined electrical output of cogeneration units 1 and 2. In addition, cogeneration unit 1 is less efficient than cogeneration unit 2 in that less electricity is produced by cogeneration unit 1 per cubic foot of natural gas consumed, relative to cogeneration unit 2. The last two columns of Table 7.2 show cost and CO₂ emissions information corresponding to each energy characteristic day for optimal economic operation. The cost and CO₂ emissions information is displayed on daily bases for each energy characteristic day in dollars per day and pounds of CO₂ per day, respectively.
The second simulation determined the best environmental mode of cogeneration plant operation for each energy characteristic day, based on minimizing CO₂ emissions. Formatted similar to Table 7.2, Table 7.3 identifies cost and CO₂ emissions information corresponding to each energy characteristic day for optimal environmental operation of the cogeneration plant. Again, we see that Cogeneration unit 1 does not operate continuously throughout the study period. This is attributed to campus electrical demand that, at times, is below the level required to both cogeneration units.
Table 7.3 – Daily cost and CO₂ emission values for environmentally optimized cogeneration plant operation from simulation based on energy characteristic days

<table>
<thead>
<tr>
<th>Energy Characteristic Day</th>
<th># Days</th>
<th>Cogen Unit 1 Operation Hours/day</th>
<th>Cogen Unit 2 Operation Hours/day</th>
<th>Greenest Day Cost $/day</th>
<th>Greenest Day Emissions lbs-CO₂ /day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christmas/New Years Break Day</td>
<td>10</td>
<td>24.00</td>
<td>24.00</td>
<td>$24,301</td>
<td>286,635</td>
</tr>
<tr>
<td>Fall Semester Weekday</td>
<td>76</td>
<td>24.00</td>
<td>24.00</td>
<td>$27,825</td>
<td>295,553</td>
</tr>
<tr>
<td>Fall Semester Weekend Day</td>
<td>28</td>
<td>0.00</td>
<td>24.00</td>
<td>$17,618</td>
<td>203,850</td>
</tr>
<tr>
<td>Non-Semester Weekday - Cooling Mode</td>
<td>5</td>
<td>13.00</td>
<td>24.00</td>
<td>$21,379</td>
<td>262,183</td>
</tr>
<tr>
<td>Non-Semester Weekday - Heating Mode</td>
<td>15</td>
<td>24.00</td>
<td>24.00</td>
<td>$20,519</td>
<td>249,252</td>
</tr>
<tr>
<td>Non-Semester Weekend Day - Cooling Mode</td>
<td>3</td>
<td>0.00</td>
<td>24.00</td>
<td>$17,256</td>
<td>214,093</td>
</tr>
<tr>
<td>Non-Semester Weekend Day - Heating Mode</td>
<td>5</td>
<td>24.00</td>
<td>24.00</td>
<td>$26,973</td>
<td>301,215</td>
</tr>
<tr>
<td>Spring Break Day</td>
<td>4</td>
<td>0.75</td>
<td>24.00</td>
<td>$15,121</td>
<td>184,319</td>
</tr>
<tr>
<td>Spring Semester Weekday</td>
<td>74</td>
<td>15.50</td>
<td>24.00</td>
<td>$18,099</td>
<td>221,169</td>
</tr>
<tr>
<td>Spring Semester Weekend Day</td>
<td>28</td>
<td>0.00</td>
<td>24.00</td>
<td>$15,070</td>
<td>190,153</td>
</tr>
<tr>
<td>Summer Session/Four-Day Weekday</td>
<td>35</td>
<td>15.00</td>
<td>24.00</td>
<td>$22,446</td>
<td>273,843</td>
</tr>
<tr>
<td>Summer Session/Four-Day Weekend Day</td>
<td>27</td>
<td>0.00</td>
<td>24.00</td>
<td>$19,387</td>
<td>233,932</td>
</tr>
<tr>
<td>University Holiday - Cooling Mode</td>
<td>3</td>
<td>0.00</td>
<td>24.00</td>
<td>$19,785</td>
<td>235,095</td>
</tr>
<tr>
<td>University Holiday - Heating Mode</td>
<td>4</td>
<td>24.00</td>
<td>24.00</td>
<td>$26,035</td>
<td>283,192</td>
</tr>
<tr>
<td>University Holiday - Mixed Mode</td>
<td>2</td>
<td>0.00</td>
<td>24.00</td>
<td>$28,376</td>
<td>281,619</td>
</tr>
<tr>
<td>Low Occupancy / Moderate Cooling</td>
<td>46</td>
<td>0.00</td>
<td>24.00</td>
<td>$18,691</td>
<td>231,463</td>
</tr>
</tbody>
</table>

Differences between the economic and environmental simulations are summarized on yearly bases below in Table 7.4. As shown, for optimal economical operation of the cogeneration plant, cogeneration unit 1 operates for 5,948 hours while cogeneration unit 2 operates continuously throughout the year. Grid purchases for the year amount to 8,117,040 kilowatt-hours. CO₂ emissions and costs for one year were 90,116,221 pounds of CO₂ and $7,601,968, respectively. This equates to $0.0843 per pound of CO₂ emissions. For optimal environmental operation, cogeneration unit 1 operates for 4,380 hours, which is 1,568 hours or 65 days less than optimal economical operation. As with optimal economic operation, cogeneration unit 2 operates continuously throughout the year. Grid purchases for the year amount to 9,809,645 kilowatt-hours. This amount of electricity is 1,692,605 kilowatt-hours more than the optimal economic scenario to make up for less electricity produced by cogeneration unit 1 operating for fewer hours. For optimal environmental operation, 89,611,551 pounds of
CO₂ are emitted. This is 504,670 pounds or 229 metric tons of CO₂ less than the optimal economic scenario. It costs $7,663,189 to operate the cogeneration plant optimally for minimized CO₂ emissions. This amount is $61,221 more than the cost to operate the cogeneration plant in the optimal economic scenario.

At $0.0855 per pound of CO₂ emissions for optimal environmental operation, a cost difference of only $0.0012 per pound of CO₂ emissions exists between optimally economic and optimally environmental operating scenarios. As a point of comparison, in 2009, Rowan University purchased New Jersey wind renewable energy certificates at a price of $0.0235 per kilowatt hour. Dividing this value by the grid emissions coefficient 0.981 pounds of CO₂ emissions per kilowatt hour, one finds that purchasing New Jersey wind renewable energy certificates results in avoiding CO₂ emissions at a cost of $0.0239 per pound of CO₂ emissions. This finding suggests and recommends that purchasing wind renewable energy certificates is more effective in reducing CO₂ emissions than switching the operation of the cogeneration plant from optimally economic to optimally environmental.

Table 7.4 – Summary of optimized economic and environmental operating scenarios of the cogeneration plant based on one year of operation.

<table>
<thead>
<tr>
<th></th>
<th>Cogen 1 Hours</th>
<th>Cogen 2 Hours</th>
<th>CO₂ Emissions, lbs</th>
<th>Cost, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least Expensive Operation</td>
<td>5,948</td>
<td>8,760</td>
<td>90,116,224</td>
<td>$7,601,974</td>
</tr>
<tr>
<td>Greenest Operation</td>
<td>4,380</td>
<td>8,760</td>
<td>89,611,626</td>
<td>$7,663,208</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Grid Purchases, kWh</th>
<th>Cogen Electricity, kWh</th>
<th>Boiler Steam, lbs</th>
<th>Cogen Steam, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least Expensive Operation</td>
<td>8,117,040</td>
<td>41,947,713</td>
<td>110,296,142</td>
<td>229,376,676</td>
</tr>
<tr>
<td>Greenest Operation</td>
<td>9,809,645</td>
<td>39,806,979</td>
<td>122,512,255</td>
<td>215,627,940</td>
</tr>
</tbody>
</table>
Figure 7.2 is a graph showing differences in annual costs between optimally economic and optimally environmental operation of the cogeneration plant. Differences in costs are indicated on the y-axis. Graduated in pounds of CO\textsubscript{2} per kilowatt-hour, the x-axis is scaled in units of CO\textsubscript{2} emissions of electricity purchased from the grid. Ranging from 0.000 to 1.600, the CO\textsubscript{2} emissions axis represents a set of values encompassing the value of 0.981 pounds of CO\textsubscript{2} emitted per kilowatt-hour of electricity selected for use in this thesis for the study period. The CO\textsubscript{2} emissions axis also encompasses values utilized during 14 trials of this sensitivity analysis. A series of curves on the graph illustrates iterations of grid electricity cost trials in units of dollars per kilowatt-hour. A range of $0.05 per kilowatt-hour to $0.30 per kilowatt-hour was selected for this illustration. This range encompassed 6 trials of this sensitivity analysis including the electricity price of $0.1372 per kilowatt-hour, selected as an average price in this thesis for the study period.

![Graph showing differences in annual costs](image)

Figure 7.2 – Differences in annual costs between optimal economic and optimal environmental operations over ranges of grid emissions and grid electricity purchase prices.
As shown in Figure 7.2, in five of six grid electricity price trials, annual cost differences were pronounced and flat for smaller grid CO₂ emissions values. For example, purchasing grid electricity at $0.20 per kilowatt-hour with a CO₂ emissions value of 0.500 pounds per kilowatt-hour will result in an annual cost difference of $5,624,549. This is indication that for lower grid CO₂ emissions values, cost differences between economically and environmentally optimal cogeneration plant operation were significant. At a grid electricity price of $0.30 per kilowatt-hour, an average cost difference of $9,820,653 resulted between economically and environmentally optimal cogeneration plant operation. As the grid becomes cleaner, annual cost differences become reduced, with an initial steep decrease at 0.8 pounds of CO₂ per kilowatt-hour to significant convergence at 1 pound of CO₂ per kilowatt-hour. At a grid electricity price of $0.05 per kilowatt-hour, there was no difference in annual cost between economically and environmentally optimal cogeneration plant operation.

Figure 7.3 below provides insight into two areas of transition of the curves shown in Figure 7.2. In Figures 7.3, 7.4, and 7.5, 448 trials of CO₂ emissions per kilowatt-hour values were executed through the program code. This provided more data points and better-defined curves for analyses of transitional areas. As shown, at 0.777 pounds of CO₂ emissions per kilowatt-hour, a steep drop in annual cost differences was observed between optimal economic and optimal environmental operations for all grid electricity prices, with the exception of $0.05 per kilowatt-hour. Between 0.777 and 0.910 pounds of CO₂ emissions per kilowatt-hour, cost differences were relatively flat. At 0.910
pounds of CO₂ emissions per kilowatt-hour, a second steep decrease was observed, followed by a region of relatively unchanging cost differences.

Figure 7.3 – Differences in annual costs between optimal economic and optimal environmental operations for transitional areas of the curves in Figure 7.1.

To gain further insight into transitional areas of the curves, Figure 7.3 shows annual cost difference curves for grid CO₂ emissions between 0.771 and 0.785 pounds per kilowatt-hour. Figure 7.3 is a detailed view of the first transition region. As shown, the first transition region consists of decreasing annual cost differences between optimal economic and environmental operations over a range of grid electricity costs. Slopes of the curves in the first transition region vary with grid electricity costs. This is indicative of convergence from larger to smaller cost differences as grid electricity costs rise and CO₂ emissions increase. At a grid electricity price of $0.05 per kilowatt-hour, there was no difference in annual cost until grid electricity CO₂ emissions reached 0.777 pounds per kilowatt-hour. Beyond this level, annual cost differences rose minimally, crossing the $0.10 per kilowatt-hour curve at 0.78 pounds of grid CO₂ emissions per hour.
Figure 7.4 – Differences in annual costs between optimal economic and optimal environmental operations at first transitional area.

Figure 7.5 below shows the second transitional area of the annual cost difference curves. At decreased annual cost differences in the range of $250,000 to $1,800,000, this transition region represents sharp decreases at 0.91 pounds of CO$_2$ emissions of grid electricity. Also at 0.91 pounds of CO$_2$ emissions of grid electricity, the annual cost difference between optimal economic and environmental operations increases from $380,000 to $500,000 for grid electricity at $0.05 per kilowatt-hour. As grid CO$_2$ emissions increase beyond this point, annual cost differences for $0.05 per kilowatt-hour electricity level off, as with the other curves. Before and after the second transition, the curves are relatively flat, indicative of cost differences that are minimal between optimal economic and environmental operations.
Figure 7.5 – Differences in annual costs between optimal economic and optimal environmental operations at second transitional area.

The differences in annual CO$_2$ emissions between optimal economic and optimal environmental operation of the campus energy system are plotted in Figure 7.6. The graph displays six trials of grid electricity costs in a plot of grid CO$_2$ emissions versus a difference in CO$_2$ emissions between optimal economic and optimal environmental operation of the cogeneration plant. The graph depicts two relatively linear regions, connected by a transition region. Low values of CO$_2$ emissions along the x-axis indicate grid electricity that is cleaner. As shown, when the grid is clean, differences in CO$_2$ emissions associated with economically and environmentally optimal cogeneration plant operation are pronounced. As an example, at a grid electricity price of $0.10 per kilowatt-hour, and a zero value for grid CO$_2$ emissions, the difference in CO$_2$ emissions between economically and environmentally optimal cogeneration plant operation is 32,486,200 pounds, or 14,735 metric tons. By changing the grid electricity price to $0.30 per kilowatt-hour, and keeping the grid CO$_2$ emissions at zero pounds per kilowatt-hour,
a difference in CO₂ emissions between economically and environmentally optimal cogeneration plant operation of 35,480,852 pounds is realized, a difference of 2,994,652 pounds, or 1,358 metric tons. As the grid becomes less clean, differences in CO₂ emissions between economically and environmentally optimal cogeneration plant operation become rapidly reduced in a linear fashion between zero and 0.8 pounds of CO₂/kWh. Beyond 0.8 pounds of CO₂/kWh, differences in CO₂ emissions reduce gradually and asymptotically to zero as grid emissions approach 2 pounds of CO₂/kWh and beyond.

Figure 7.6 – Differences in annual CO₂ emissions between optimal economic and optimal environmental operation over ranges of grid emissions and electricity purchase prices.

To gain further insight into transition area of the curves, Figure 7.7 shows annual CO₂ emissions difference curves for grid CO₂ emissions between 0.650 and 1.000 pounds per kilowatt-hour. As shown, in the transition region, the curves remain parallel and trend in a similar fashion, with the exception of the grid electricity price of $0.05 per
kilowatt-hour. When the grid is very clean and least expensive, there is no difference in CO₂ emissions between optimal economic and optimal environmental campus energy systems operations. Holding the grid electricity price of $0.05 per kilowatt-hour, as the grid becomes less clean, linear increases in CO₂ emissions between optimal economic and optimal environmental campus energy systems operations become more pronounced. For grid electricity is $0.10 and above, differences in CO₂ emissions between optimal economic and optimal environmental campus energy systems operations vary little through the full range of zero to 1.7 pounds of CO₂ emissions of grid electricity.

Figure 7.7 – Differences in annual CO₂ emissions between optimal economic and optimal environmental operation at the transition region.

Figure 7.8 below is a plot showing the cost of CO₂ emissions per pound over ranges of grid CO₂ emissions and grid electricity purchase prices. At grid CO₂ emissions levels of 0.5 pounds per kilowatt-hour or less, and for the entire range of grid electricity purchase prices evaluated, the cost of CO₂ was at or below $0.68 per pound. As the grid became less clean, the cost of CO₂ per pound curves diverged reaching peaks that appeared to be coincident. A peak of $3.34 per pound of CO₂ emissions was reached for
a trial grid electricity price of $0.30 per kilowatt-hour. As the grid became less clean beyond the $3.34 per pound of CO$_2$ emissions peak, there was a steep decrease in cost per pound of CO$_2$ followed by small increases and a second steep decrease. Two transition areas were identified for further examination.

Figure 7.8 – Cost per pound of CO$_2$ emissions over ranges of grid emissions and electricity purchase prices.

To get a sense of the cost per pound of CO$_2$ emissions of optimal operation of the campus energy system, Figure 7.9 is similar to Figure 7.8, with the exception of the y-axis, which is graduated over a much smaller range. As shown, the y-axis ranges from zero to $0.20 per pound of CO$_2$ emissions, a fraction of the corresponding range in Figure 7.8. This illustration is a comparison of optimal campus energy system operation with purchasing renewable energy certificates and a projection of the social cost of carbon from the Interagency Working Group on the Social Cost of Carbon. The top horizontal thick black line represents the 2014 year-to-date average New Jersey solar renewable energy certificate (SREC) price. An average SREC price of $165.00 per
megawatt-hour was obtained from SREC Trade, Inc. This price was converted into kilowatt-hour units and converted to pounds of CO₂ emissions through division by the grid emissions coefficient of 0.981 pounds per kilowatt-hour. The horizontal thick black line at $0.0585 per pound of CO₂ emissions represents the projected social cost of carbon for 2020 from the Interagency Working Group on the Social Cost of Carbon. The horizontal thick black line at $0.0239 per pound of CO₂ emissions represents the contracted price Rowan University paid for New Jersey wind renewable energy certificates (WRECs) in 2009. As shown, purchasing renewable energy certificates is more cost effective than decommissioning cogeneration units 1 and 2.

Figure 7.9 – Comparison of cost per pound of CO₂ emissions with renewable energy certificate prices and projected social cost of carbon by the Interagency Working Group on the social cost of carbon.

Figure 7.10 below is a representation of the first transition region shown in Figure 7.8. At a grid emissions level of 0.785 pounds per kilowatt-hour, peak CO₂ per pound costs were identified for grid electricity costs of $0.10 per kilowatt-hour or greater. The first transition consisted of a steep linear decrease in CO₂ per pound costs over a range of
0.773 to 0.777 pound per kilowatt-hour. At a grid emissions level of 0.777 pounds per kilowatt-hour and beyond, the cost of CO₂ curves remained flat for the selected range of grid costs and CO₂ emissions with the exception of a grid electricity cost of $0.05 per kilowatt-hour. At $0.05 per kilowatt-hour, CO₂ costs per pound increased in an inverse manner, relative to the other curves, through the transition region. Beyond the peak at 0.777 pounds of CO₂ emissions per kilowatt-hour, the cost of CO₂ per pound decreased in a non-linear manner for grid electricity costing $0.05 per kilowatt-hour.

Figure 7.10 – Cost per pound of CO₂ emissions over the range of grid emissions for the first transition region.

The second transition region is shown in Figure 7.11. The second transition region involved smaller changes in costs of CO₂ per pound. As a result, the scale for the y-axis was reduced for improved observation of data trends. Curves associated with grid electricity costs of $0.10 per kilowatt-hour or greater decreased non-linearly from 0.800 to 0.824 pounds of CO₂ emissions per kilowatt-hour. CO₂ costs per pound then increased in a non-linear manner between 0.824 and 0.910 grid CO₂ emissions per kilowatt-hour. From 0.800 to 0.910 pounds of CO₂ emissions per kilowatt-hour, CO₂
costs per pound associated with $0.05 per kilowatt-hour grid electricity costs decreased in a non-linear manner. At grid emissions values of 0.910 pounds per kilowatt-hour or greater, all CO₂ cost per pound curves decreased gradually and were at or below $0.295 per pound of CO₂ emissions.

It should be noted that in general, the grid changes in cost of operation and CO₂ emissions through a typical day. As demand changes, utilities respond by starting up or shutting down generation equipment. For example, in the middle of a typical summer day, peak-shaving generation equipment will be brought online by regional transmission operators to meet rapid changes in demand. Peak-shaving generation equipment includes gas-fired reciprocating generators because of their rapid start capabilities. However, reciprocating generators are typically less efficient than their turbine counterparts. In addition, reciprocating turbines emit higher rates of CO₂ emissions. Starting up and shutting down various generation equipment results in marginal cost differences and CO₂ emissions grid throughout the day. As a sizeable community of energy users, Rowan
University represents a significant load to add to, or remove from, the grid, as opposed to residences. As such, it is important that campus energy systems operations decisions be made with simultaneous and real time knowledge of economic and environmental considerations.

7.7 Reliability and Emergency Preparedness

Beyond economic and environmental performance, the cogeneration plant provides a level of electrical and thermal reliability to the Rowan University campus. Should there be a disruption of the electric utility to the campus, the cogeneration plant can provide approximately 4.7 megawatts of electricity to the campus. Although the campus electrical demand can double at peak usage times, the cogeneration plant can provide the required demand to meet critical campus electrical loads during emergencies. This includes loads associated with emergency lighting, alarm systems, fire protection systems, and other critical building systems, critical boiler plant loads, elevators, health care facilities, and communications systems. Should the need arise, a black-start emergency generator at the cogeneration plant is capable of providing electricity for starter motors and excitation windings for both cogeneration units when power to the campus has been disrupted. During such circumstances, campus electricians would open circuit breakers at buildings, implementing selective load reduction strategies. This action would ensure that the cogeneration plant provides only power for critical campus loads and that the load capability of the cogeneration plant is not exceeded.
In 2011, Rowan University was activated as a regional evacuation center during hurricane Irene. In this role, Rowan University became a temporary residence for evacuees. As it is possible to again fulfill this role similarly for future emergency events, providing space with lighting, heat, medical services, food and water for mass gatherings, Rowan University can utilize the cogeneration plant to provide electricity and heat as described above.
Chapter 8

Summary and Conclusions

This section provides a summary and conclusions developed in this thesis. As stated at the beginning of this thesis, the objective of this thesis was to determine the optimal operation of energy conversion and production subsystems through minimization of economic and environmental costs and to evaluate how changing electrical grid costs and sources will affect future optimal operations. This thesis has accomplished these objectives. There are five major conclusions we can make from the efforts that went into the development of this thesis. Detailed below, the conclusions include a comparison of year 2007 and 2009, the development of energy characteristic days, daily consumption that is not unusual, minor differences between least expensive and greenest cogeneration plant operation, addressing future changes in grid quality and cost, and favorability of the cogeneration plant for economics and the environment.

In FY07, the campus used 41,194,911 kilowatt-hours of electricity and 245,866,586 pounds of steam. This includes electricity and steam utilized by the central chiller plant. Table 8.1 below is a comparison years 2007 and 2009. As shown, electricity demand increased from 2007 to 2009. Similarly, steam usage decreased from 2007 to 2009.

<table>
<thead>
<tr>
<th>Year</th>
<th>Electricity Usage kWh</th>
<th>Steam Usage lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>41,194,911</td>
<td>245,866,586</td>
</tr>
<tr>
<td>2009</td>
<td>50,383,290</td>
<td>319,963,943</td>
</tr>
</tbody>
</table>

Table 8.1 – Comparison of campus electricity and steam usages for years 2007 and 2009
Table 8.2 below shows purchased utilities and total CO₂ emissions in pounds for years 2007, 2009, and the simulated optimal economic and optimal environmental operational scenarios. As shown, year 2007 was a year involving less fuel oil and natural gas purchases than in 2009. However, grid electricity purchases were higher in 2007 than in 2009. In 2007, Rowan University’s first cogeneration plant was in the process of being decommissioned. It would be expected that during this time, less electricity was being generated on campus. Therefore, grid electricity purchases would have had to increase to meet campus demand. CO₂ emissions were less in 2007 than in 2009. With less electricity production on campus and use of smaller grid CO₂ emissions coefficient, CO₂ emissions were lower in 2007 compared to 2009. Purchased utilities and CO₂ emissions values for optimal economic and optimal environmental operations were compared to 2007 and 2009 values, also shown in Table 8.2. As expected, subtle differences were found between the two optimized operations. The results were consistent that for the least expensive operation, more natural gas is purchased, less grid electricity is purchased, and CO₂ emissions were greater than for greenest operation. Conversely, for greenest operation, less natural gas is purchased, more grid electricity is purchased, and CO₂ emissions were less.

Table 8.2 – Purchased utilities and CO₂ emissions for years 2007, 2009, and simulated optimal operations

<table>
<thead>
<tr>
<th>Year</th>
<th>Fuel Oil, Gal.</th>
<th>Natural Gas, CF</th>
<th>Grid Electricity, kWh</th>
<th>CO₂ Emissions, Pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 Actual</td>
<td>47,811</td>
<td>369,691,901</td>
<td>38,684,195</td>
<td>73,366,838</td>
</tr>
<tr>
<td>2009 Actual</td>
<td>76,509</td>
<td>550,898,289</td>
<td>26,028,266</td>
<td>79,255,179</td>
</tr>
<tr>
<td>Least Expensive Operation</td>
<td>-</td>
<td>683,752,641</td>
<td>8,117,040</td>
<td>90,116,224</td>
</tr>
<tr>
<td>Greenest Operation</td>
<td>-</td>
<td>666,130,678</td>
<td>9,809,645</td>
<td>89,611,626</td>
</tr>
</tbody>
</table>
It can be concluded that in 2007, a reduction in on-campus electricity production resulted when the first cogeneration unit was decommissioned. As a result, decreases in natural gas purchases, coupled with increases in grid electricity purchases, occurred. In 2007, grid electricity costs were $5,092,378 and natural gas costs were $4,157,332. With increased grid purchases and usage of a lower grid CO₂ emissions coefficient, a value of 73,366,838 pounds of CO₂ emissions was established. Increased on-campus electricity and steam production resulted in higher CO₂ emissions. Marginal differences between optimal economic and optimal environmental operations were found in this analysis.

To characterize daily campus activities and the impact the activities had on campus energy consumption, it was necessary to define blocks of representative academic days that were initially referred to as academic characteristic days. An academic characteristic day represents a group of days that are similar to each other, with respect to types of activities on campus. By studying the academic characteristic days and integrating campus energy usage data into the study, 16 characteristic days were developed. The characteristic days were utilized in a model to simulate and predict economic and environmental performance of the cogeneration plant. Characteristic day values were within 4% of actual campus annual electricity and steam usages. The shapes of hourly and daily energy curves were in agreement, indicating high usages in day and low usages at night. To simplify the analysis further, the number of characteristic days could be reduced as long as the general distribution is reproduced. A recommended reconfiguration of characteristic days is shown in Table 8.3 below.
Table 8.3 – Potential reconfiguration of characteristic days for future studies.

<table>
<thead>
<tr>
<th>Campus Use</th>
<th>Hot</th>
<th>Mild</th>
<th>Cold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class in Session</td>
<td>April Weekday</td>
<td>October Weekday</td>
<td>December Weekday</td>
</tr>
<tr>
<td>Students on campus</td>
<td>April Weekend</td>
<td>October Weekend</td>
<td>December Weekend</td>
</tr>
<tr>
<td>no classes</td>
<td>Summer</td>
<td>Spring Break</td>
<td>Winter Break</td>
</tr>
<tr>
<td>Students off campus</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An alternate method of typifying days would be to prepare degree-day analyses. Although the use of degree-day analyses for calculations is a more traditional approach than developing characteristic days, degree-days too have limitations. For example, heating and cooling requirements for buildings are not always linear with outdoor temperatures.

During review of the energy data provided to this thesis, daily energy consumption for the campus was determined to be not unusual. As this thesis studied the first commissioned year of cogeneration plant operation, this base year represented a new operating paradigm for a system that was configured with two units. However, campus demand did not change, allowing campus behavior to be profiled. These findings provided assistance the development of characteristic days. The period of study in the main topic of this thesis involved weather conditions characterized by a mild winter and hot summer. Ideally, analysis of a second set of data including another year of purchasing, production, and consumption data would serve as further validation of the model. For alternate year data associated with weather conditions that differ from this study, it is anticipated that hours of operation and characteristic days would require adjustments in magnitude. In addition, magnitudes of costs and CO₂ emissions would be expected to differ. However, plant equipment efficiencies would not be expected to
change. Further, fundamental changes in overall trends and conclusions would not be expected. In addition, changes in campus size and population would impact the results of similar studies and is beyond the scope of this thesis. It is anticipated that analyses of overall costs and CO$_2$ emissions between optimally economic and optimally environmental scenarios, conducted in alternate years, would permit comparison, despite weather differences.

Using the analytical model, it was found that purchasing electricity from the grid and operating the boilers is more expensive than simultaneous operation of both cogeneration units at full capacity by the amount of $303.19 per hour, provided there is sufficient campus demand for the electricity and steam produced. The analytical model also determined that, at current grid electricity and natural gas prices, cogeneration units 1 and 2, operated in any combination, is less expensive that purchasing electricity from the grid and producing steam from campus boilers. It can be concluded that, at current grid electricity and natural gas prices, cogeneration unit utilization is less expensive than purchasing equivalent amounts of electric and gas to produce steam, as long as there is sufficient campus demand for the electricity and steam produced.

The analytical model determined that purchasing electricity from the grid and operating the boilers is slightly cleaner than operating cogeneration unit 1 at full capacity by 156.06 pounds of CO$_2$ per hour. Operating cogeneration unit 2 resulted in 44.61 pounds of CO$_2$ emissions per hour less than shutting down cogeneration unit 2, purchasing electricity from the grid, and supplementing the steam with the boilers. This
difference indicated that, at full capacity, operating cogeneration unit 2 is slightly cleaner than purchasing electricity from the grid. Purchasing electricity from the grid and operating the boilers is slightly cleaner than simultaneous operation of cogeneration units 1 and 2 at full capacity. Cogeneration Unit 1 was slightly less clean than purchasing electricity from the grid and operating the boilers. Cogeneration Unit 2 was cleaner than purchasing electricity from the grid and operating the boilers, with both cogeneration units within a 10% difference. It can be concluded that cogeneration unit utilization was nearly the same for CO₂ emissions as purchasing equivalent amounts of electric and gas to produce steam.

Executing the program code produced more nuanced operating scenarios that kept all three boilers in a continuous state of readiness. In addition, the program code suggested operating cogeneration unit 2 continuously throughout the study period, with cogeneration unit 1 operating with less duration the extent of which, was driven by optimal economical versus optimal environmental operations. The least expensive operation for one year was $7,601,974 with 90,116,224 pounds of CO₂ emissions. The greenest operation was $7,663,208 with 89,611,626 pounds of CO₂ emissions.

Through simulation of economic and environmental performance of the cogeneration plant, differences between the least expensive and greenest optimal operations were found to be minor. By making minor changes in operating protocol and minimal added costs, the cogeneration plant can be operated in such a way that it favors environmental performance by reducing CO₂ emissions.
As the cost and environmental quality of grid electricity has changed since its inception during the industrial age, it will continue to change in the future. The US Energy Information Administration is predicting a reduction in electricity generated by coal and nuclear technologies as plants retire in the next 20 years. As renewable types of energy continue to expand their presences on the grid, environmental profiles of grid electricity will continue to evolve. Technological change in renewable energy is accelerating its growth and impact to reducing CO₂ emissions in ways that cannot be predicted far in advance. At the same time, hydraulic fracturing is accelerating natural gas exploration and production, particularly in the Marcellus shale regions of the United States. By utilizing hydraulic fracturing, production of natural gas has more than quadrupled in the last decade using this technology. As fossil fuel production and renewable power generation facilities continue to expand, possible outcomes of CO₂ emissions profiles include a grid that is cleaner, dirtier, or unchanging. According to the US Energy Information Administration, the CO₂ emissions profile of the grid is not likely to change significantly over the remaining life of the cogeneration plant as shown in Figure 8.1 below.
Similarly, costs for grid electricity have evolved over time and will continue to evolve, also at levels that cannot be predicted far in advance. History tells us that over time, grid prices have increased, with smaller decreases over smaller periods. It is likely that the overall upward trend will continue over the remaining life of the cogeneration plant. This thesis provides a means for evaluating the operation of the cogeneration plant as the cost and environmental quality of grid electricity continues to change in the future.

The sensitivity study demonstrated that, for changing grid emissions values and projected future grid costs, over the life cycle of the current cogeneration plant, it is not anticipated that grid emissions will become clean enough to merit decommissioning of cogeneration plant early.
This thesis has identified the relatively small degrees of differences at which the cogeneration plant operates with consideration to economics and the environment. This thesis has also identified new choices for operating cogeneration plant equipment and the economic and environmental impact that come with the new choices. It can be concluded that operation of the cogeneration plant is favorable for both economical and environmental considerations.
References


Appendix A: Computer Programming Code

% Opti5_1
% version history:
% Opti1: first program accounted for electric use for a given electric demand
% Opti2: added steam generation for given electric and steam demand
% Opti2_1: calculated steam from co-gen
% Opti2_2: calculated steam from co-gens and boiler1 and 2
% Opti2_3: includes error trapping to limit boilers to capacity, and
%   prevent negative grid purchases
% Opti2_4: calculates the prices in dollars and CO2 for best of the four
%   possibilities for given electric and steam demand
% Opti3: Looks for optimal use throughout the day.
% Opti3_1: Reads in demand in 15 minute increments, and outputs optimal use
% Opti3_2: Updates values for parameters elecprod, steamprod, gasuse, gascost,
%   electriccost, and electricCO2.
% Opti3_3: Provides error trapping
% Opti3_4: Calculates daily totals of mincost, greencostofcheapest, costofgreenest,
% and mingreencost.
% Opti3_5: Converts all time-based parameters to quarter-hour bases, consistent
% with input file format.
% Opti3_6: Returns time-based program parameters to hourly bases and corrects
% daily totals.
% Opti3_7: Initializes all totalizing values to zero prior to program loops.
% Opti5: Totals values for the full year.
% Opti5_1: First cut at looping through 15 characteristic days
% Opti6: Cycles through different costs and CO2 coefficients for electricity
% %
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% variables
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% system inputs
% %
% vectors refer to [cogen1,cogen2,boiler1,boiler2,boiler3,grid]
% %
elecprod and steamprod define the production of electricity and steam at capacity
% elecprod=[1357,3867,0,0,0,1]; %electrical capacity in kilowatts
steamprod=[8724,20260,26000,40000,40000,0]; %thermal capacity in pounds of steam per hour
% gasuse defines the use of natural gas to run the cogen and boilers at capacity
%
gasuse=[20.575,48.819,31.941,47.847,46.948,0]; % gas usage at capacity in MCF/hour
(griduse=[0,0,0,0,0,1];
gascost=9.5242; % cost in dollars per unit of gas, $/MCF
gasCO2=120.593; % CO2 emission per unit of gas, lb CO2/MCF of gas
% electriccost % cost in dollars of electricity per kilowatt hour, $/kW-Hr
% electricCO2 % CO2 emission per kilowatt-hour of electricity, lb CO2/kW-Hr
%
%--------------------------------------------------------------------------------------------
% define boiler capacities as their own variables
%
boiler1cap=steamprod(3);
boiler2cap=steamprod(4);
boiler3cap=steamprod(5);
%
%--------------------------------------------------------------------------------------------
% Set up characteristic days
%
% day1 Fall Semester Weekday (120809)
% day2 Fall Semester Weekend Day (101009)
% day3 Spring Semester Weekday (030310)
% day4 Spring Semester Weekend Day (031310)
% day5 Spring Break Day (031710)
% day6 Summer Session Weekday (070610)
% day7 Summer Session Weekend Day (071010)
% day8 Non-semester Weekday - Cooling Mode (081910)
% day9 Non-semester Weekday - Heating Mode (010910)
% day10 Non-Semester Weekend Day - Cooling Mode (082810)
% day11 Non-Semester Weekend Day - Heating Mode (011110)
% day12 University Holiday - Cooling Mode (053110)
% day13 University Holiday - Heating Mode (112709)
% day14 University Holiday - Mixed Mode (110309)
% day15 Christmas/New Years Break (122809)
% day16 Low Occupancy/Moderate Cooling (080810)

Daysperyear=[76,28,74,28,4,35,27,5,5,3,15,3,4,2,10,46]; % # of each characteristic day/year
%--------------------------------------------------------------------------------------------
% Open Input and output files
%--------------------------------------------------------------------------------------------
% fday1 = fopen('120809Input.prn','r')
% fday2 = fopen('101009Input.prn','r')
% fday3 = fopen('030310Input.prn','r')
% fday4 = fopen('031310Input.prn','r')
% fday5 = fopen('031710Input.prn','r')
fid2 = fopen('C02difference.txt','w')
fid3 = fopen('Costdifference.txt','w')
fid4 = fopen('CostofC02.txt','w')

% Write header to fid2
% 
fprintf(fid2,"CO2 difference \n")
fprintf(fid2,"\n")
fprintf(fid2," Carbon Difference in C02 (pounds) \n")
fprintf(fid2," Emissions \n")
fprintf(fid2," (lb/kW hour) Cost of Electricity ($/kW hour) \n")
fprintf(fid2," 0.05 0.10 0.15 0.20 0.25 0.30 \n")

% Write header to fid3
% 
fprintf(fid3,"Cost difference \n")
fprintf(fid3,"\n")
fprintf(fid3," Carbon Difference in Cost ($) \n")
fprintf(fid3," Emissions \n")
fprintf(fid3," (lb/kW hour) Cost of Electricity ($/kW hour) \n")
fprintf(fid3," 0.05 0.10 0.15 0.20 0.25 0.30 \n")

% Write header to fid4
% 
fprintf(fid4,"Cost of CO2 \n")
fprintf(fid4,"\n")
fprintf(fid4," Carbon Cost of C02($/lb) \n")
fprintf(fid4," Emissions \n")
fprintf(fid4," (lb/kW hour) Cost of Electricity ($/kW hour) \n")
fprintf(fid4,"                  0.05        0.10        0.15        0.20        0.25        0.30         
");
% 
for i = [1:14];
electricCO2 = (i-1)*0.125
Results1 = [0.0,0.0,0.0,0.0,0.0,0.0,0.0];
Results2 = [0.0,0.0,0.0,0.0,0.0,0.0,0.0];
Results3 = [0.0,0.0,0.0,0.0,0.0,0.0,0.0];
for j = [1:6];
electriccost = (j)*0.05
%---------------------------------------------------------------
----
% Totaling variables
% equipop=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];       % use of cogen1,2; boilers
1,2,3; grid
cheapest_day_totalCO2 = 0;                    % daily total of CO2 emissions for
cheapest operation
cheapest_day_cost = 0;                       % daily total of $ for cheapest
operation
greenest_day_totalCO2 = 0;                   % daily total of CO2 emissions for
greenest operation
greenest_day_cost = 0;                       % daily total of $ for greenest
operation
cheapest_year_totalCO2 = 0;                  % yearly total of CO2 emissions for
cheapest operation
cheapest_year_cost = 0;                      % yearly total of $ for cheapest
operation
greenest_year_totalCO2 = 0;                 % yearly total of CO2 emissions for
greenest operation
greenest_year_cost = 0;                     % yearly total of $ for greenest
operation
greenest_day_op_total=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];
cheapest_day_op_total=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];
dailyelectricdemand = .0;
dailysteamdemand = 0.0;
yearlyelectricdemand = 0.0;
yearlysteamdemand = 0.0;
greenest_year_op_total=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];
cheapest_year_op_total=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];
%---------------------------------------------------------------
----
% Loop through all 16 characteristic days
% 
for day = [1:16];
if (day == 1)
    fid1 = fopen('120809Input.prn','r')
end
if (day == 2)
    fid1 = fopen('101009Input.prn','r')
end
if (day == 3)
    fid1 = fopen('030310Input.prn','r')
end
if (day == 4)
    fid1 = fopen('031310Input.prn','r')
end
if (day == 5)
    fid1 = fopen('031710Input.prn','r')
end
if (day == 6)
    fid1 = fopen('070610Input.prn','r')
end
if (day == 7)
    fid1 = fopen('071010Input.prn','r')
end
if (day == 8)
    fid1 = fopen('081910Input.prn','r')
end
if (day == 9)
    fid1 = fopen('010910Input.prn','r')
end
if (day == 10)
    fid1 = fopen('082810Input.prn','r')
end
if (day == 11)
    fid1 = fopen('011110Input.prn','r')
end
if (day == 12)
    fid1 = fopen('053110Input.prn','r')
end
if (day == 13)
    fid1 = fopen('112709Input.prn','r')
end
if (day == 14)
    fid1 = fopen('110309Input.prn','r')
end
if (day == 15)
    fid1 = fopen('122809Input.prn','r')
end
if (day == 16)
    fid1 = fopen('080810Input.prn','r')
end
%
% Read data in from fid1
% start with 8 lines of text
% assumes 4th line is used as header for output file.
%
foo = fgetl(fid1);
foo = fgetl(fid1);
foo = fgetl(fid1);
foo4 = fgetl(fid1);
foo = fgetl(fid1);
foo = fgetl(fid1);
foo = fgetl(fid1);

%------------------------------------------------------------------------------
----------
% Initialize all daily totalizing values to zero
%
cheapest_day_totalCO2 = 0;          % daily total of CO2 emissions
for cheapest operation
cheapest_day_cost = 0;                          % daily total of $ for
cheapest operation

% daily total of CO2 emissions
for greenest operation
%
greenest_day_totalCO2 = 0;          % daily total of CO2 emissions
greenest_day_cost = 0;                          % daily total of $ for
greenest operation
%
% input datafile is in 15 minute increments
% => need to loop through 96 time steps to get full day
%
for timestep = [1:96];
    %
    % read one line of 15 minutes of data
    %
    date = fscanf(fid1,'%c',[9]);
    time = fscanf(fid1,'%c',[4]);
    foo = fscanf(fid1,'%f',[4]);
    foo2 = fscanf(fid1,'
');
    electdemand = foo(3);
steamdemand = foo(4);  
dailyelectricdemand = dailyelectricdemand+electdemand*0.25;  
dailysteamdemand = dailysteamdemand+steamdemand*0.25;  

% loop through 4 permutations of cogens on or off  
mincostperhour = 2000000;  
minglecostperhour = 20000000;  
for cogen1=[0,1]  
    for cogen2=[0,1]  
        % start by assuming boilers on low, zero grid purchase  
        equipop=[cogen1,cogen2,0.05,0.05,0.05,0];  
        % calculate electric and steam deficits for original assumption  
        elecgen=dot(equipop,elecprod);  
        steamgen=dot(equipop,steamprod);  
        electdeficit = electdemand-elecgen;  
        steamdeficit = steamdemand-steamgen;  
        % update boiler and grid to account for deficits  
        equipop(6) = electdeficit;  
        equipop(4)=equipop(4)+(steamdeficit/(2.0*boiler2cap));  
        equipop(5)=equipop(5)+(steamdeficit/(2.0*boiler3cap));  
        % begin error trapping  
        if equipop(6) < 0.0;  
            equipop(6) = 0;  
        end  
        if equipop(5) < 0.05  
            equipop(5) = 0.05;  
        end  
        if equipop(4) < 0.05  
            equipop(4) = 0.05;  
        end  
        if equipop(3) < 0.05  
            equipop(3) = 0.05;  
        end  
        if equipop(3) > 1.0;  
            equipop(3) = 1.0;  
        end
\[ \text{steamdeficit} = \text{steamdemand} - \text{dot}(\text{equipop,steamprod}); \]
\[ \text{equipop}(3) = \text{equipop}(3) + \frac{\text{steamdeficit}}{\text{boiler1cap}}; \]
\[ \text{if} \ \text{equipop}(3) > 1.0; \]
\[ \text{equipop}(3) = 1.0 \]
\[ \% \text{ cannot meet demand, add big cost penalty} \]
\[ \text{cost} = 1000000; \]
\[ \text{greencost} = 1000000; \]
\[ \text{end} \]
\[ \% \]
\[ \% \text{ calculate costs of option} \]
\[ \text{totalgas} = \text{dot}(\text{gasuse,equipop}); \]
\[ \text{totalgrid} = \text{dot}(\text{griduse,equipop}); \]
\[ \text{cost} = \text{totalgas} \times \text{gascost} + \text{totalgrid} \times \text{electriccost}; \]
\[ \text{greencost} = \text{totalgas} \times \text{gasCO2} + \text{totalgrid} \times \text{electricCO2}; \]
\[ \% \]
\[ \% \text{ check to see if this is cheapest or greenest option} \]
\[ \text{if} \ \text{cost} < \text{mincostperhour}; \]
\[ \text{mincostperhour} = \text{cost}; \]
\[ \text{greencostofcheapestperhour} = \text{greencost}; \]
\[ \text{cheapestop} = \text{equipop}; \]
\[ \text{end} \]
\[ \% \]
\[ \% \text{ greenest option so far} \]
\[ \text{if} \ \text{greencost} < \text{mingreencostperhour}; \]
\[ \text{mingreencostperhour} = \text{greencost}; \]
\[ \text{costofgreenestperhour} = \text{cost}; \]
\[ \text{greenestop} = \text{equipop}; \]
\[ \text{end} \]
\[ \% \]
\[ \% \text{ add } 0.25 \text{ times hourly rates to daily totals} \]
\[ \text{cheapest\_day\_op\_total} = \text{cheapest\_day\_op\_total} + 0.25 \times \text{cheapestop}; \]
greenest_day_op_total = greenest_day_op_total + 0.25*greenestop;

cheapest_day_cost=cheapest_day_cost+0.25*mincostperhour;

cheapest_day_totalCO2=cheapest_day_totalCO2+0.25*greencostofcheapestperhour;

greenest_day_totalCO2=greenest_day_totalCO2+0.25*mingreencostperhour;

greenest_day_cost=greenest_day_cost+0.25*costofgreenestperhour;
end
%
% update yearly totals
%

yearlyelectricdemand=yearlyelectricdemand+dailyelectricdemand*Daysperyear(day);

yearlysteamdemand=yearlysteamdemand+dailysteamdemand*Daysperyear(day);

cheapest_year_op_total=cheapest_year_op_total+cheapest_day_op_total*Daysperyear(day);

greenest_year_op_total=greenest_year_op_total+greenest_day_op_total*Daysperyear(day);

cheapest_year_cost=cheapest_year_cost+cheapest_day_cost*Daysperyear(day);

cheapest_year_totalCO2=cheapest_year_totalCO2+cheapest_day_totalCO2*Daysperyear(day);

greenest_year_totalCO2=greenest_year_totalCO2+greenest_day_totalCO2*Daysperyear(day);

greenest_year_cost=greenest_year_cost+greenest_day_cost*Daysperyear(day);
% fclose(fid1);
end

Results1(j)=Results1(j)+cheapest_year_totalCO2-greenest_year_totalCO2;
Results2(j)=Results2(j)+greenest_year_cost-cheapest_year_cost;
Results3(j)=Results3(j)+(greenest_year_cost-cheapest_year_cost)/(cheapest_year_totalCO2-greenest_year_totalCO2);
end
fprintf(fid2,' %10.3f  %10.1f  %10.1f  %10.1f  %10.1f  %10.1f  %10.1f
',electricCO2,
Results1(1),Results1(2),Results1(3),Results1(4),Results1(5),Results1(6));
fprintf(fid3,' %10.3f  %10.1f  %10.1f  %10.1f  %10.1f  %10.1f  %10.1f
',electricCO2,
Results2(1),Results2(2),Results2(3),Results2(4),Results2(5),Results2(6));
fprintf(fid4,' %10.3f  %10.3f  %10.3f  %10.3f  %10.3f  %10.3f  %10.3f
',electricCO2,
Results3(1),Results3(2),Results3(3),Results3(4),Results3(5),Results3(6));
% end
close(fid2);
close(fid3);
## Appendix: Primary Plant Equipment Data

<table>
<thead>
<tr>
<th>I. Cogeneration Turbogenerator Unit # 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominally Rated Electrical Power Output</td>
<td>1.2 Megawatt</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Solar Turbines, Inc.</td>
</tr>
<tr>
<td>Model</td>
<td>Saturn 20</td>
</tr>
<tr>
<td>Serial Number</td>
<td>SG05N74</td>
</tr>
<tr>
<td>Year Built</td>
<td>2006</td>
</tr>
<tr>
<td>Sales Order Number</td>
<td>2-76932</td>
</tr>
<tr>
<td>Generator Output</td>
<td>1,210 Kilowatts</td>
</tr>
<tr>
<td>Mechanical Drive Output</td>
<td>1,185 Kilowatts</td>
</tr>
<tr>
<td>Mechanical Drive Output</td>
<td>1,590 Horsepower</td>
</tr>
<tr>
<td>Highest Supply Ratings, VAC/φ/AMP</td>
<td>460/3/102</td>
</tr>
<tr>
<td>Highest Supply Ratings, VDC/AMP</td>
<td>30/1.3</td>
</tr>
<tr>
<td>Generator, VAC/φ/Hz/kW</td>
<td>4,160/3/60/1,360</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. Cogeneration Turbogenerator Unit # 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominally Rated Electrical Power Output</td>
<td>3.5 Megawatt</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Solar Turbines, Inc.</td>
</tr>
<tr>
<td>Model</td>
<td>Centaur 40</td>
</tr>
<tr>
<td>Serial Number</td>
<td>CG05964</td>
</tr>
<tr>
<td>Year Built</td>
<td>2006</td>
</tr>
<tr>
<td>Sales Order Number</td>
<td>2-76931</td>
</tr>
<tr>
<td>Generator Output</td>
<td>3,515 Kilowatts</td>
</tr>
<tr>
<td>Mechanical Drive Output</td>
<td>3,500 Kilowatts</td>
</tr>
<tr>
<td>Mechanical Drive Output</td>
<td>4,700 Horsepower</td>
</tr>
<tr>
<td>Highest Supply Ratings, VAC/φ/AMP</td>
<td>460/3/337</td>
</tr>
<tr>
<td>Highest Supply Ratings, VDC/AMP</td>
<td>120/13</td>
</tr>
<tr>
<td>Generator, VAC/φ/Hz/kW</td>
<td>12,470/3/60/4,750</td>
</tr>
</tbody>
</table>
### III. Heat Recovery Steam Generator # 1

<table>
<thead>
<tr>
<th>Equipment integrated with</th>
<th>Cogeneration Turbogenerator Unit # 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Design Steam Capacity</td>
<td>8,300 pounds per hour</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Rentech Boiler Systems, Inc.</td>
</tr>
<tr>
<td>Purchase Order Number</td>
<td>P6003805</td>
</tr>
<tr>
<td>Year Built</td>
<td>2006</td>
</tr>
<tr>
<td>Maximum Allowable Working Pressure</td>
<td>250 psig at 500°F; Tubes 700°F</td>
</tr>
<tr>
<td>1st Stage MFG Service Number</td>
<td>2005-117</td>
</tr>
<tr>
<td>1st Stage Heating Surface Square Feet</td>
<td>7,562</td>
</tr>
<tr>
<td>2nd Stage MFG Service Number</td>
<td>2005-116</td>
</tr>
<tr>
<td>2nd Stage Heating Surface Square Feet</td>
<td>809</td>
</tr>
</tbody>
</table>

### IV. Heat Recovery Steam Generator # 2

<table>
<thead>
<tr>
<th>Equipment integrated with</th>
<th>Cogeneration Turbogenerator Unit # 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Design Steam Capacity</td>
<td>19,550 pounds per hour</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Rentech Boiler Systems, Inc.</td>
</tr>
<tr>
<td>Purchase Order Number</td>
<td>P6003805</td>
</tr>
<tr>
<td>Year Built</td>
<td>2006</td>
</tr>
<tr>
<td>Maximum Allowable Working Pressure</td>
<td>250 psig at 500°F; Tubes 700°F</td>
</tr>
<tr>
<td>1st Stage MFG Service Number</td>
<td>2005-121</td>
</tr>
<tr>
<td>1st Stage Heating Surface Square Feet</td>
<td>15,459</td>
</tr>
<tr>
<td>2nd Stage MFG Service Number</td>
<td>2005-119</td>
</tr>
<tr>
<td>2nd Stage Heating Surface Square Feet</td>
<td>1,803</td>
</tr>
</tbody>
</table>
### V. Natural Gas Compressor # 1

(Provides Compressed Natural Gas to Cogeneration Turbogenerator Unit #1)

<table>
<thead>
<tr>
<th>Location</th>
<th>Outdoor, North Side of Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Configuration</td>
<td>Enclosed Skid-Mounted Compressor Coupled with Pre-Engineered Auxilliary Systems</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Frick</td>
</tr>
<tr>
<td>Model/Serial Number</td>
<td>XJF120521G3DDZ</td>
</tr>
<tr>
<td>Manufacture Date</td>
<td>2006</td>
</tr>
<tr>
<td>Type of Compressor</td>
<td>Rotary Screw</td>
</tr>
<tr>
<td>RPM</td>
<td>3,600</td>
</tr>
<tr>
<td>Volume Ratio</td>
<td>2.2 - 5.0</td>
</tr>
<tr>
<td>Swept Volume at Maximum Speed</td>
<td>296 Feet per minute</td>
</tr>
<tr>
<td>Maximum Allowabe Pressure</td>
<td>350 psig</td>
</tr>
<tr>
<td>Exchanger Manufacturer</td>
<td>York</td>
</tr>
<tr>
<td>Exchanger Serial Number</td>
<td>155053</td>
</tr>
<tr>
<td>Driver</td>
<td>Electric Motor</td>
</tr>
<tr>
<td>Motor Horsepower</td>
<td>100 Horsepower</td>
</tr>
</tbody>
</table>

### VI. Natural Gas Compressor # 2

(Provides Compressed Natural Gas to Cogeneration Turbogenerator Unit #2)

<table>
<thead>
<tr>
<th>Location</th>
<th>Outdoor, North Side of Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Configuration</td>
<td>Enclosed Skid-Mounted Compressor Coupled with Pre-Engineered Auxilliary Systems</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Frick</td>
</tr>
<tr>
<td>Model Number</td>
<td>RWF 11 134H</td>
</tr>
<tr>
<td>Serial Number</td>
<td>0494</td>
</tr>
<tr>
<td>Manufacture Date</td>
<td>June 12, 2006</td>
</tr>
<tr>
<td>Sales Order Number</td>
<td>28401401000</td>
</tr>
<tr>
<td>Refrigerant Type</td>
<td>R-50</td>
</tr>
<tr>
<td>Driver</td>
<td>Induction Electric Motor</td>
</tr>
<tr>
<td>Motor Manufacturer</td>
<td>Siemens</td>
</tr>
<tr>
<td>Motor Horsepower</td>
<td>300 Horsepower</td>
</tr>
<tr>
<td>VII. Boiler # 1</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Boiler Manufacturer</td>
<td>Superior Combustion Industries, Inc.</td>
</tr>
<tr>
<td>Manufacturer Location</td>
<td>Wilkes Barre, PA</td>
</tr>
<tr>
<td>Boiler Type</td>
<td>Water Tube</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Dual: Natural Gas and #2 Fuel Oil</td>
</tr>
<tr>
<td>H.S.B</td>
<td>2583</td>
</tr>
<tr>
<td>National Board Number</td>
<td>2583</td>
</tr>
<tr>
<td>Capacity</td>
<td>26,000 pounds of steam per hour</td>
</tr>
<tr>
<td>Heat release per cubic foot</td>
<td>53,500</td>
</tr>
<tr>
<td>Furnace Volume</td>
<td>654</td>
</tr>
<tr>
<td>Year Built</td>
<td>1960</td>
</tr>
<tr>
<td>Working Pressure</td>
<td>250 Psig</td>
</tr>
<tr>
<td>Heating Surface</td>
<td>3,083</td>
</tr>
<tr>
<td>Serial Number</td>
<td>2583 3716</td>
</tr>
<tr>
<td>NJ Number</td>
<td>21374</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>VIII. Boiler # 2</td>
<td></td>
</tr>
<tr>
<td>Boiler Manufacturer</td>
<td>Babcock &amp; Wilcox, a McDermott Company</td>
</tr>
<tr>
<td>Manufacturer Location</td>
<td>West Point, Mississippi</td>
</tr>
<tr>
<td>Boiler Type</td>
<td>Water Tube</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Dual Fuel: Natural Gas and #2 Fuel Oil</td>
</tr>
<tr>
<td>Efficiency Feature</td>
<td>Stack Economizer</td>
</tr>
<tr>
<td>National Board Number</td>
<td>25199</td>
</tr>
<tr>
<td>B&amp;W Number</td>
<td>201-3403</td>
</tr>
<tr>
<td>Boiler MAWP</td>
<td>250 psi at 366° F</td>
</tr>
<tr>
<td>Capacity - MDSC</td>
<td>40,000 pounds per hour</td>
</tr>
<tr>
<td>Boiler Heating Surface</td>
<td>3,063 square feet</td>
</tr>
<tr>
<td>Waterwall Heating Surface</td>
<td>543 square feet</td>
</tr>
<tr>
<td>Year Built</td>
<td>2004</td>
</tr>
<tr>
<td>Erected by</td>
<td>Frank Lill &amp; Son (Rochester, NY)</td>
</tr>
<tr>
<td>Erect Date</td>
<td>January, 2005</td>
</tr>
</tbody>
</table>
### IX. Boiler # 3

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Manufacturer</td>
<td>Babcock &amp; Wilcox, a McDermott Company</td>
</tr>
<tr>
<td>Manufacturer Location</td>
<td>West Point, Mississippi</td>
</tr>
<tr>
<td>Boiler Type</td>
<td>Water Tube</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Dual Fuel: Natural Gas and #2 Fuel Oil</td>
</tr>
<tr>
<td>Efficiency Feature</td>
<td>Stack Economizer</td>
</tr>
<tr>
<td>National Board Number</td>
<td>25200</td>
</tr>
<tr>
<td>B&amp;W Number</td>
<td>201-3404</td>
</tr>
<tr>
<td>Boiler MAWP</td>
<td>250 psi at 366° F</td>
</tr>
<tr>
<td>Capacity - MDSC</td>
<td>40,000 pounds per hour</td>
</tr>
<tr>
<td>Boiler Heating Surface</td>
<td>3,063 square feet</td>
</tr>
<tr>
<td>Waterwall Heating Surface</td>
<td>543 square feet</td>
</tr>
<tr>
<td>Year Built</td>
<td>2004</td>
</tr>
<tr>
<td>Erected by</td>
<td>Frank Lill &amp; Son (Rochester, NY)</td>
</tr>
<tr>
<td>Erect Date</td>
<td>January, 2005</td>
</tr>
</tbody>
</table>

### X. Steam Turbine-Driven Centrifugal Chiller

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominally Rated Thermal Power Output</td>
<td>2,400 Tons</td>
</tr>
<tr>
<td>Chiller Manufacturer</td>
<td>York International Corp.</td>
</tr>
<tr>
<td>Chiller Model Number</td>
<td>YSTXFXDJ5-KD2000125-13-1.061-35216C-FS</td>
</tr>
<tr>
<td>Compressor Model Number</td>
<td>YDHA-104VDD</td>
</tr>
<tr>
<td>Refrigerant Charge, R134a</td>
<td>5,810 pounds</td>
</tr>
<tr>
<td>Serial Number</td>
<td>896610</td>
</tr>
<tr>
<td>Electric Supply Voltage</td>
<td>460 VAC</td>
</tr>
<tr>
<td>Turbine Manufacturer</td>
<td>Tuthill/Murray</td>
</tr>
<tr>
<td>Turbine Model Number</td>
<td>KD2000125</td>
</tr>
<tr>
<td>Turbine Rated Horsepower</td>
<td>1,994 Horsepower</td>
</tr>
<tr>
<td>Supply Steam Pressure</td>
<td>150 psig</td>
</tr>
<tr>
<td>Exhaust Steam Pressure</td>
<td>3.85 psig</td>
</tr>
<tr>
<td>Steam Condensor Manufacturer</td>
<td>ITT Standard</td>
</tr>
<tr>
<td>Steam Condensor Model Number</td>
<td>35216C</td>
</tr>
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</table>
### XI. Electric Motor-Driven Centrifugal Chiller # 1

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominally Rated Thermal Power Output</td>
<td>1,060 tons</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Trane, Inc.</td>
</tr>
<tr>
<td>Model Name</td>
<td>CVHF1060</td>
</tr>
<tr>
<td>Model Number</td>
<td>CVHF106GA2MOPCW279AE9LCEBC00000000YA1004CL0W0003A100A</td>
</tr>
<tr>
<td>Serial Number</td>
<td>L05D01947</td>
</tr>
<tr>
<td>Manufacture Date</td>
<td>October 5, 2005</td>
</tr>
<tr>
<td>Sales Order Number</td>
<td>D2U929A</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>480 Volts</td>
</tr>
<tr>
<td>Number of Phases</td>
<td>3</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hertz</td>
</tr>
<tr>
<td>Nominal Electric Power</td>
<td>595 Kilowatts</td>
</tr>
<tr>
<td>Compressor Motor Voltage</td>
<td>480 Volts</td>
</tr>
<tr>
<td>Compressor Motor Rated Amperage</td>
<td>844 Amps</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>R-123</td>
</tr>
<tr>
<td>Field Charge</td>
<td>2,200 Pounds</td>
</tr>
<tr>
<td>High Side Max Working Pressure</td>
<td>15 psig</td>
</tr>
<tr>
<td>Low Side Max Working Pressure</td>
<td>15 psig</td>
</tr>
</tbody>
</table>

### XII. Electric Motor-Driven Centrifugal Chiller # 2

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominally Rated Thermal Power Output</td>
<td>1,060 tons</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Trane, Inc.</td>
</tr>
<tr>
<td>Model Name</td>
<td>CVHF1060</td>
</tr>
<tr>
<td>Model Number</td>
<td>CVHF106GA2MOPCW279AE9LCEBC00000000YA1004CL0W0003A100A</td>
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<tr>
<td>Serial Number</td>
<td>L05D01975</td>
</tr>
<tr>
<td>Manufacture Date</td>
<td>October 5, 2005</td>
</tr>
<tr>
<td>Sales Order Number</td>
<td>D2U929B</td>
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<tr>
<td>Rated Voltage</td>
<td>480 Volts</td>
</tr>
<tr>
<td>Number of Phases</td>
<td>3</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hertz</td>
</tr>
<tr>
<td>Nominal Electric Power</td>
<td>595 Kilowatts</td>
</tr>
<tr>
<td>Compressor Motor Voltage</td>
<td>480 Volts</td>
</tr>
<tr>
<td>Compressor Motor Rated Amperage</td>
<td>844 Amps</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>R-123</td>
</tr>
<tr>
<td>Field Charge</td>
<td>2,200 Pounds</td>
</tr>
<tr>
<td>High Side Max Working Pressure</td>
<td>15 psig</td>
</tr>
<tr>
<td>Low Side Max Working Pressure</td>
<td>15 psig</td>
</tr>
</tbody>
</table>