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TEAM COGENERATION TECHNOLOGY

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ABSTRACT

The global environmental crisis has given rise to a myriad of recent research initiatives directed at the reduction of carbon emissions. The vast majority of these investigations are currently focused on harnessing alternative energy sources, with minimal resources devoted to refining existing cogeneration, or combined heat and power (CHP) systems, and even less attention paid to those powering university campuses. The proposed research objective is twofold: 1) to develop a model CHP system that best meets the energy needs of a generic university campus while minimizing carbon emissions, and 2) to recommend specific improvements to the University of Maryland's cogeneration system. The first problem will be approached using a combination of thermodynamic simulations and economic calculations; the second will be addressed through a detailed case study. Future research may broaden these findings and apply them to other universities or incorporate evolving energy technologies.

1.0. Research Introduction

1.1. Introduction

Humanity's consumption of hydrocarbon fossil fuels has given rise to the current environmental crisis. An overwhelming body of scientific evidence points to human-induced emissions of greenhouse gases as a direct cause of destructive environmental effects, including rising sea levels, a shrinking ice cap, unpredictable weather patterns, and species extinction (Alley 1). In addition to the environmental costs of global warming, the potential economic costs and social implications for human life are enormous, ranging from agricultural changes to alterations in population distributions and disease patterns (Stern 52).

Long-term solutions to these problems will have to address the fundamental need to reduce society's carbon footprint. It has been estimated that U.S. carbon dioxide emissions from fossil fuel burning alone totaled 5,984 million metric tons in 2007 (U.S. Energy Information Administration 3). As large universities proliferate and expand in the United States, their total carbon output will become appreciable. Coupled with the necessity that colleges remain on the cutting edge of intellectual and social movements, there is strong cause for schools to reevaluate their environmental footprint.

At the University of Maryland College Park (UMD), important steps have already been taken by administrators to translate the goal of reduced carbon emissions into a viable plan of action. The American College & University Presidents Climate Commitment, signed in early 2007 by leaders of more than 284 institutions across the country, including UMD President Dan Mote, represents a collective commitment to carbon neutrality by the year 2050 (American College & University Presidents Climate Commitment).

While these agreements are integral to reducing carbon emissions, the process is complex and requires a much more specific plan of action for each individual campus. The first issue that must be addressed by any establishment striving towards carbon neutrality is the decision between reductions and offsets. A reduction approach involves the physical curtailment of carbon emissions from an institution's power producing systems, and a reduction of overall energy consumption. Conversely, an offset approach involves the purchase of carbon credits from nonpolluting entities (clean energy or carbon sequestration) to negate the output of the purchasing institution. It is the focus of this study to reduce physical carbon emissions.

There are a number of clean energy systems available in today's market. Solar, wind, and nuclear systems are three "carbon neutral" power production alternatives. However, these alternatives prove unfeasible for most university's to take advantage of (an issue addressed later in section 2.2.). Combined Heat and Power (CHP) systems are not necessarily free of carbon emissions, but they do dramatically increase fuel efficiency by utilizing both the electricity and waste heat created during energy production. This increase in energy efficiency decreases fuel consumption, and in turn, decreases carbon emissions. While the improvement of its CHP systems would not immediately transition a university to complete carbon neutrality, its economic feasibility as opposed to its alternatives makes it a striking candidate for power production.

Practicality remains a large factor in determining the method in which a university tackles carbon reduction. Initially, change will be gradual; it would be impossible to abandon fossil fuels immediately since most universities have significant investments in their current energy systems and system lines. To stay within the confines of university budgets, fossil fuel burning plants continue to be built in order to satisfy the growing energy needs of college campuses.

Although there is widespread acknowledgement of environmentally friendly alternatives, most remain impractical. Emerging technologies, however, make it possible to construct new plants that have smaller carbon footprints while remaining economically viable.

CHP systems are designed to make use of the waste heat given off during the power production process. By extracting exhaust heat and producing steam, cogeneration systems can supply heating, cooling or additional power to a nearby region. While the vast majority of current CHP systems combust fossil fuels and release a positive net amount of carbon into the atmosphere, they are considerably more efficient (and less polluting) than traditional power cycles. In the initial stages of a university's plan to reduce carbon emissions, the implementation of a well-designed CHP system can dramatically cut carbon emissions and even function as a transitional step towards full carbon neutrality.

1.2. Research Questions

The proposed research methodology is guided by two overarching and interrelated research questions. First, to what extent can a large university campus with access to a district heating system meet its energy needs through an economical Combined Heat and Power (CHP) system while minimizing carbon emissions? Second, what CHP system is best suited for the University of Maryland (UMD) when considering energy demands, carbon footprint, specific location variables, and economic constraints? As research proceeds, many sub-questions will arise and be addressed accordingly. These two overarching questions, however, encompass the vast majority of issues that will be considered during the research process.

2.0. Review of Literature

2.1. Technological Development of Cogeneration Systems

Thomas Edison is widely credited with creating the first cogeneration energy plant at the 1882 Pearl Street Station. Just two years later, in 1884, a district heating system was used to heat the Del Coronado Hotel in San Diego.

By the 1900s, steam turbine generators began to replace the traditional reciprocating engines. This shift resulted in increased efficiency. Turbine designers, in a race to meet burgeoning energy demands, began building larger steam turbine engines. By 1932, generating efficiencies increased from 3.7% to 16.5% in 1902 ("Combined Heat and Power"). Since coal was used as a main energy source for the first half of the 20th century, power plants emitted a great deal of pollution. Public pressure forced these power plants to relocate to remote areas. Accordingly, cogeneration became impractical, as the heat that was captured had no applications in isolation. Furthermore, users of large quantities of electricity did not also demand a significant supply of steam, making cogeneration impractical in most cases. These factors combined to keep electrical energy and heat energy separate commodities well into the 1960s.

In the late 1960s, steam turbine technology was beginning to be replaced by combustion turbine technologies. When the two technologies were combined, in a process known as a combined cycle, efficiencies of up to 60% were achieved. However, the accelerated development and widespread adoption of cogeneration technology did not occur in earnest until the late 1970s. A number of factors coincided with the explosion of cogeneration onto the energy scene. These factors included the passing of the PURPA Act in 1978, ballooning energy prices as a result of the oil crisis, and the public's increasing awareness of environmental issues (Sirchis 63). Although the price of oil settled after the oil crisis, the continued existence of inflated fuel prices along with greater emphasis on equipment efficiency has allowed CHP to remain a viable option for power generation.

2.2. Fuel Sources

The production costs associated with different energy sources fluctuate greatly throughout the course of every day, every week, every month, and every year. Consequently, it is very hard to give precise numbers relating how much one energy source costs in relation to all the others. Current technology has enabled a wide variety of fuel sources to be utilized for power and steam production, resulting in many variables to consider and to account for in any thorough energy production analysis. Among the potential fuel sources for a CHP system, there are both renewable and non-renewable options that support a different balance of carbon emissions, energy production capacity (daily hours energy can be produced), and energy production costs.

2.2.1. Wind & Solar Power

Given the right conditions, wind and solar power are excellent options for sustainable, clean energy. For high quality wind sites, production costs can be as low as $0.03-0.05/kWh, but for lower mean annual velocities (~5m/s) production costs can range as high as $0.10–0.12/kWh. Photovoltaic power generation, with production costs as high as $0.20-0.40/kWh may seem unfeasible, but photovoltaic panels offer the ability to offset transmission costs and losses through distributed generation. The most useful quality, from an environmental standpoint, is that both sources' carbon emissions are 0g/kWh (Sims 1318-1319). Any feasible model for harnessing either power source would include numerous wind turbines in a windy off-campus location or installation of solar panels in open areas to utilize the light energy on campus.

Despite the inherent advantages of these clean technologies, both power sources are impractical for the sustained demands of a large university campus. The amount of power capable of being generated varies greatly throughout the day and provides only nominal energy at peak consumption times (Kellogg 72). The fact that wind and solar energy are both converted directly into electricity and then transmitted to the university campus also eliminates the possibility of cogeneration – the production of steam from waste heat. Any steam demanded for a campus heating system would have to be produced by electric boilers, thus increasing the electricity demand, causing a surge in required capital investment, and rendering both energy sources impractical for a campus power system.

2.2.2. Biomass Power

Biomass is an emerging renewable fuel source that can be utilized to produce power through either gasification and combustion (~$0.0398/kWh) or direct incineration (~$0.055/kWh) of unprocessed plant-based products, yielding 0g/kWh net carbon emissions (Sims 1319). Both options provide distinct advantages: the ability to cogenerate steam and electricity, high overall efficiency, low costs and low emissions. Biomass used in these plants include "agricultural and forestry residues, landfill gas, municipal solid wastes and energy crops" (Sims 1318-9). As a result, given a sustainable supply of locally available feedstock, such systems have potential as reliable sources of power and to be included in an efficient model of a campus power plant.

2.2.3. Nuclear Power

Nuclear power provides massive quantities of energy with zero carbon emissions during operation with power generating costs of $0.039-0.080/kWh (Sims 1319). The goal of this research, however, is to develop a cogeneration system that provides a true net reduction in carbon output, as opposed to simply purchasing carbon credits or power from a nuclear plant and maintaining the same carbon footprint. Therefore, nuclear power and other carbon-offset options are not considered in this study.

2.2.4. Coal Power

Coal power is a nonrenewable, low-cost source of energy that produces 38% of the power generated in the world today, more than any other two energy sources combined (Sims 1316). Production costs depend largely upon the method of combustion utilized: \$0.049/kWh for Pulverized Fuel (PF) combustion and \$0.036-0.060 for Integrated Gasification Combined Cycle (IGCC). Unfortunately these technologies are relatively high producers of carbon, with emissions at 229g/kWh and 190-198g/kWh, respectively. The inclusion of carbon capture technology does reduce carbon emissions to 40g/kWh, but increases the operational costs of both to \$0.079/kWh (Sims 1316, 1321). Coal provides inexpensive, reliable power, but produces much higher levels of carbon emissions and pollutants than any other fuel source. Given that the project's goal is to develop a plan that is both cost-efficient and environmentally beneficial, coal power will not be discussed further.

2.2.5. Natural Gas Power

Natural gas power is one of the cleanest nonrenewable sources of energy with generating costs for a combined cycle gas turbine ranging from \$0.049-0.069/kWh and carbon emissions from 103-122g/kWh. Employing similar carbon capture technologies as with coal plants, emissions can be reduced to 17g/kWh while generation costs rise to \$0.064-0.084/kWh (Sims 1317). With the ability to be rapidly constructed and expanded into a complete cogeneration plant, combined cycle gas turbine systems are the "highly favored option where gas is available at reasonable prices" (Sims 1317). For this reason, natural gas fired, cogeneration plants are the main focus of this article.

2.3. Cogeneration System Design & Components

2.3.1. Cogeneration System Overview

Cogeneration, or combined heat and power (CHP), systems are designed to produce both electricity using a standard turbine system and steam using the waste heat created in the process. The electricity can be used locally or transferred to the electric grid and the steam is commonly distributed to nearby buildings through a district heating system for the purposes of heating, cooling, and hot or chilled water.

Three fundamental components comprise CHP systems: a heat source (heater, combustion chamber, or boiler), a turbine coupled to a generator, and a heat recovery steam generator (HRSG). The boiler or combustion chamber converts the chemical energy in the fuel into kinetic energy in the working fluid (air or water) via heat transfer. The working fluid exits the heater or combustion chamber at significantly higher temperatures and pressures as compared to when it enters. The turbine extracts energy from the working fluid and turns a generator to produce electricity. The working fluid exits the heater or combustion chamber at significantly higher temperatures and pressures as compared to when it enters. The HRSG is a heat exchanger that extracts some of the remaining heat from the working fluid and transfers it to a separate water cycle to produce steam. This steam can be run through a turbine to produce more electricity or used for other purposes, such as distributed heating and hot water production.

Gas-fired turbines are one of the most common prime movers in cogeneration systems. Standard gas turbine systems operate in a Brayton cycle that involves the intake and compression of fresh air, the injection and combustion of fuel for heat production, expansion of the fuel / air mixture through the gas turbine which powers the generator, and exhausting of the remaining heated gas. Turbine systems of this nature require the cheapest capital investment of nearly all power production systems, and modified cycles with higher thermal efficiencies present opportunities for long-term economic gains and reduced environmental impact.

2.3.2. Cycle Modification Overview

There exist a broad range of cycle improvements and modifications that can be made to a standard cogeneration system to improve its thermal efficiency and power output. Three specific modifications – reheat, recuperation, and intercooling – are given the largest focus in academic research because they are effective and firmly established ideas that have been tested in industrial applications.

Reheat involves processing the exhaust of a first-stage turbine in a second-stage turbine for additional power extraction. Between the two turbines, exhaust temperature is increased by injecting and combusting supplemental natural gas to the stream. The effectiveness of this modification depends on the pressure and oxygen content of the first-stage turbine exhaust stream (Moran 477).

Recuperation, also commonly referred to as regeneration, involves heating the compressed air before it is combusted by passing it through a heat exchanger with the turbine exhaust gases. Raising the initial air temperature decreases the amount of fuel necessary to bring the gases up to the turbine operating temperature, thereby decreasing the running costs and total emissions.

Thermal efficiency can also be increased by decreasing the required work of compression through a process known as intercooling. Such a process usually involves two stages of compression. The air is water-cooled after the first stage to decrease its volume and thus decrease the work required to compress it further in the second stage (Moran 479).

Any combination of these three cycle improvements can be employed in the design of a more efficient cogeneration system.

2.3.3. Research in Cycle Improvements

Bhargava et al. present an approach for conducting thermo-economic analyses of cogeneration systems. They conclude that intercooled reheat (ICRH) recuperated cycles, when compared to nonrecuperated ICRH, recuperated, and simple Brayton cycles, present the highest available thermal efficiency and energy savings index (ESI) at full load, in addition to the lowest penalty in electrical efficiency and ESI under partial load operation. For moderate and low-load applications (5-20 MW), the researchers conclude that nonrecuperated ICRH cycles provide the highest return on investment under full and partial-load application throughout the range of fuel, steam, and electricity prices considered in the study, despite its poorer thermodynamic performance when compared to the recuperated ICRH cycle. This difference is mainly attributed to higher equipment costs for the recuperated ICRH cycle (Bhargava 881-91).

Similar articles have developed mathematical models to describe the effects different cycle modifications have on overall thermal efficiency. General theoretical tools have been developed to model the operation of power cycles with multi-stage reheating and intercooling that consider compressor and turbine isentropic efficiencies and heat exchanger efficiency. Such designs give optimized pressure ratios, maximum power output and maximum efficiency for a specific cycle design (Hernandez 1462). Simulations have also been developed for analyzing the efficiency of regeneration in a combined cycle (Evenko 308). Such models, which consider the operation of separate cycle components, may be incorporated into a holistic model for this study.

2.3.4. Pinch Analysis

The concept of energy pinch is a rigorous approach to minimizing inefficiencies in industrial processes and is often applied in the development of combined heat and power systems. In a pinch analysis, processes are defined as either sources or sinks of energy, representing supply and demand respectively. The ultimate goal is to match each sink with a suitable source based on the quality of energy required and the quality available. Minimum theoretical utility requirements are calculated for each process and matched to an energy source that is closest to—while being reliably above—the target. In the example of heating systems, low quality and low temperature steam can be used to adequately heat and cool buildings in the vicinity of production. Pinch therefore dictates that only low quality steam be used in this application, reserving higher quality energy sources for more demanding applications like energy extraction in a steam-driven turbine.

A fundamental tool in pinch analysis is a composite curve, which plots a process' heat availability with the process' heat demands. These curves are ultimately used to determine a level of minimum energy consumption.

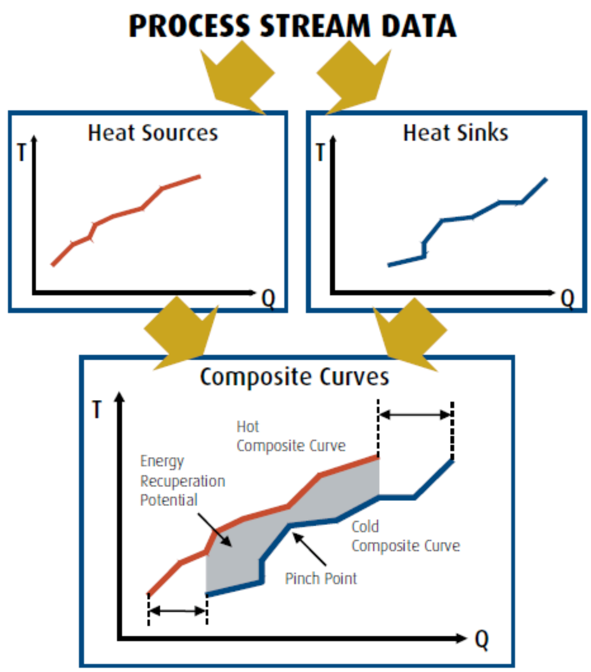

Figure 2.3.4.1: Composite Curve Creation (Government of Canada)

The overlap between these two curves on the horizontal axis describes the total amount of heat recovery possible. To find the pinch point, the cold curve is progressively moved toward the hot curve in a horizontal direction. Because the horizontal axis measures relative quantities, this translation does not change the actual process values themselves. The curves are moved closer together until a minimum allowable temperature difference is reached, as determined by the minimum temperature difference acceptable to a heat exchanger. At this point, the horizontal overlap of the curves is greater than when they were initially drawn, increasing the amount of recoverable heat. The remaining heating and cooling needs are the minimum hot utility requirement (Q_{Hmin}) and minimum cold utility requirement (Q_{Cmin}).

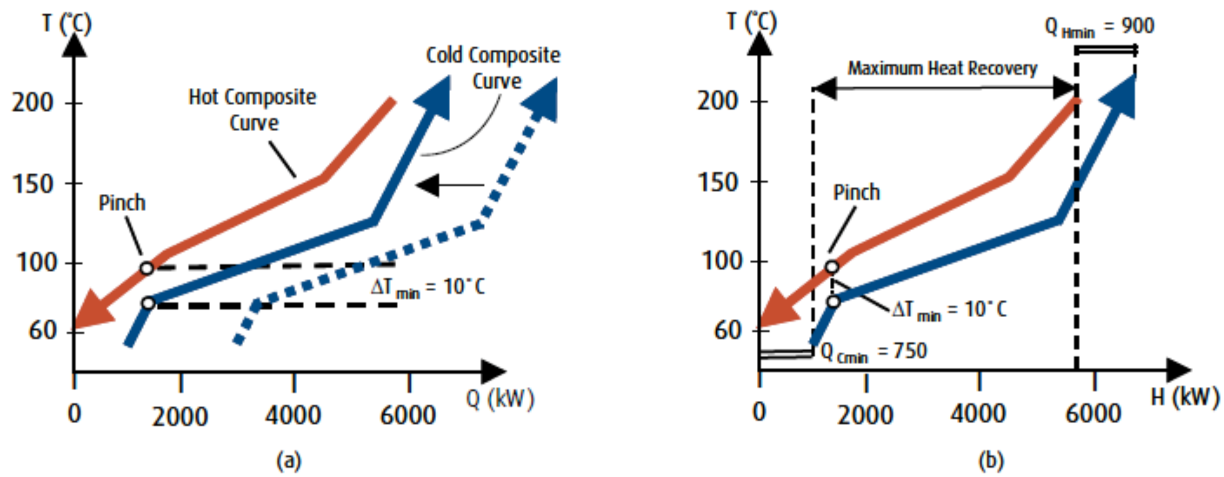

Figure 2.3.4.2: A Graphical Representation of Pinch (Government of Canada)

This process allows for the determination of maximum energy savings before the heat exchanger network is every designed (Government of Canada).

2.4. Computer Modeling Software

The most reliable data for a research project on power generation cycles would be performance data from operating gas turbine engines. However, working with physical machinery would be expensive, cumbersome, and impractical. Thermodynamic modeling software has emerged as a reliable surrogate tool, providing solid data upon which researchers can draw valid conclusions about theoretical designs.

Significant improvements have been made to combustion modeling capabilities since the early 1970s in terms of its empirical correlations (Mongia 1). Computer modeling has not been able to achieve the degree of accuracy that empirical methods (such as development testing on either bench-top or full-scale equipment) provide. However, modeling has still been successful in advancing development of cycle technologies while reducing the time and money put into development of new combustion products (Mongia 1). In fact, the widespread use of computer modeling in academic research has demonstrated the possibility of significant increases in existing turbine cycle efficiencies. As of February 2008, the most advanced combined cycle power plants in operation can achieve efficiencies of no greater than 60%, but thermodynamic simulations have demonstrated the possibility of achieving efficiencies of over 62% using a variety of equipment modifications and cycle performance enhancements (Sanjay 541).

Considering logistical limitations and the benefits of computer modeling, an optimized design for this research project will be based on both empirical data and computer modeling simulations. Empirical data will be collected from contacts at universities across the nation with CHP systems that run on natural gas and have similar load needs to the University of Maryland. Based upon these performance data, an optimized CHP system design for this project will be generated, simulated, and tested using simulation software called GSP (Gas turbine Simulation Program). GSP is a component-based modeling environment that allows for the steady state simulation of almost any gas turbine configuration. It is the primary tool for gas turbine performance analysis for the National Aerospace Laboratory, an independent technological institute that carries out applied research on behalf of aviation and space sectors. A free, fully functional version (GSP LE) can be downloaded from the GSP website. This combination of empirical data with computer modeling will provide the most comprehensive means of developing a cogeneration system that fits the needs and demands of a generic large university.

2.5. Policy

While it is important to consider engineering specifications and fuel issues during the design process of a CHP plant, it is also necessary to consider all relevant policies and regulations. The proposed design of a CHP plant may have optimal engineering specifications but if it does not conform to federal regulations the work will be rendered immediately impractical. This is why it is important to closely examine existing federal and local policies that will affect a future CHP plant on the University of Maryland campus.

One of the most influential federal policies was the Public Utilities Regulatory Policies Act (PURPA) of 1978. PURPA has been called the most prominent of a significant number of conservationist bills passed by Congress in response to the 230% increase in oil prices during the previous decade (Kolanowski 11). PURPA mandated that utility companies were required to purchase power from designated “qualifying facilities” (QF), at the utility's avoided cost of producing power. To be named a qualifying facility a cogeneration plant was required to meet selected criteria, as designated in Section 201 of PURPA and enforced by the Federal Energy Regulatory Committee (FERC). The primary point of consideration for a plant attempting to become a QF was the production of electric energy and steam, heat, or another form of energy from the same primary fuel. In addition, the plant was required to meet other specified standards that regulated ownership of the plant, its operating policies, and minimum efficiency levels (Hu 178). The primary purpose of PURPA was to alleviate some of the issues that had previously been detrimental to cogeneration facilities. In requiring utilities to buy power from a CHP plant, even if only applicable under certain conditions, PURPA helped QFs immensely by allowing them to profit from the sale of their power. In addition, other clauses within PURPA allowed cogenerators to more easily interconnect to the grid, purchase backup power at reasonable rates, and to exempt themselves from certain federal and state utility regulations (Hu 178). In Section 1253 of the Energy Policy Act of 2005, Section 210 of PURPA was amended with the purpose of ensuring the environmental integrity of future cogeneration plants. A final revision of the policy by FERC was released in 2006 and stated that contemporary cogeneration facilities must demonstrate their intent to produce power efficiently and for permitted purposes. Through these significant revisions to PURPA, FERC has proven its commitment to allow CHP to remain a viable and practical alternative for those choosing to self-produce power.

2.6. Economics

The economic viability of a CHP system makes it an attractive choice for university power generation purposes. With the addition of the environmental cost of carbon to the economic analysis of a new power system, universities are given further incentive to explore cogeneration. Because this research focuses on reducing carbon emissions, a cost will be attached to carbon dioxide (CO_2) output. This cost will be derived from a series of existing valuations made by highly qualified researchers.

There have been several studies on the social cost of carbon emissions. Each utilized different cost determination methods and the results have been heavily varied (Hope 565). Several efforts, including *The Stern Review*, have cited high social costs of carbon emissions—up to $312 per ton (Stern 212). Such interpretations have taken heavy criticism, and many argue that these reports are fear-pandering, overemphasizing the damages caused by carbon emissions in order to encourage action (Stone 20). Due to apparent variability in assessing the cost of carbon, this study will assume a more conservative value of $30 per ton of carbon emissions (Nordhaus 11). This value of $30 per ton has been estimated by Professor William Nordhaus, a Yale University economist. Dr. Nordhaus is considered to be one of, if not the, "leading economist in the climate change field. (Solomon)" This value of carbon costs was determined through a complex computer modeling system and is relatively aligned with current carbon credit costs as well (Lomborg).

In recent times, there has been a significant amount of economic controversy over the need for an immediate response to the current climate situation. The Stern Review puts the significance of reducing carbon emissions in a global context and demonstrates the need for immediate changes to avoid drastic, irreversible damage to the Earth (Stern 52). The Stern Review quantifies the severity of potential environmental effects of current emission levels by utilizing economic modeling systems that take into account ecological, social, and economic effects. The review indicates that a 20% reduction in international Gross Domestic Product (GDP) will result from carbon emissions within the next couple decades, assuming current emission rates continue (Stern 1). Critics of the report, however, note that this 20% reduction in GDP was calculated using a near-zero social discount rate, meaning that this value incorporates distant future expenses. These expenses are so distant that they may occur in the 23rd or 24th century (Reynolds). In addition to this, Dr. Nordhaus also argues that with this near-zero discount rate, an immediate cost of seven trillion dollars, 15% of world consumption, would have to be spent today in order to solve a .01% drop in output in the year 2200 caused by carbon emissions. In contrast to the drastic changes called upon by the Stern Review, Dr. Nordhaus, as well as other leading environmental economists argue that the better solution to the carbon crisis is to slowly introduce long term carbon reducing measures (Reynolds).

The main reason that the estimates of the carbon costs are so varied is that there are an extraordinarily large number of factors that are affected by carbon emissions. Different methods for determining the carbon cost use different variables with different values. However, there are several key factors that are generally used by all estimates of carbon costs. Most experts recognize that there will be a significant impact on agriculture, though there are disagreements on the degree of this impact. Certain areas are expected to experience improved agricultural conditions due to increased sunlight and rainfall, while other areas are expected to be negatively affected. However, according to Intergovernmental Panel on Climate Change (IPCC), food production in Africa and many arid regions is projected to significantly decrease, in some regions by as much as 50% by 2020 (13). The IPCC also specifically mentions Australia, New Zealand, and Latin America as regions that will experience decreases in food production, though North America is expected to have increases in agriculture in the first few decades of this century (13-15).

Perhaps the largest potential expense from global warming caused by carbon emissions is the increase in natural disasters. According to a study by the UNEP Finance Initiatives, a group consisting of two of the largest insurance companies in the world, worldwide economic damages due to natural disasters are doubling every ten years, and annual losses will reach almost $150 billion next decade (1). These damages affect all members of society, and the sheer size of the estimated expense warrants detailed research into methods for curbing such damages. Changing temperatures are also expected to have negative impacts on infrastructure, especially older infrastructure which was not built to adapt to temperature changes. Some experts believe that global warming hinders the opportunity for underdeveloped countries to increase their economic development, especially considering these countries are less prepared for increases in natural disasters. While no one can be certain of the exact total cost or sources of loss from increasing carbon emissions, experts agree that the costs will be significant for people worldwide, as carbon emissions may result in major economic losses.

Regardless of which economic theory one chooses to subscribe to, the fact remains that carbon emissions must be reduced. One particular long term solution to this issue is installing a more efficient CHP system. As an institution of progressive leaders, a university must take the first step in standing against carbon emissions.

2.7. University of Maryland

The University of Maryland, College Park has publicly committed to reduce its carbon footprint. President Mote signed the President's Climate Commitment, a joint effort by a number of U.S. universities to reduce the emissions of campuses nationwide. Recently, a collection of approaches to carbon reduction and a set of reduction goals, the UMD Climate Action Plan, was drafted. This plan also involves the creation of a special committee to evaluate strategies for the University's goal of carbon neutrality by 2050 (Tilley 2). Among other standards cited in the plan, the University adopted the Leadership in Energy and Environmental Design (LEED) Silver standard in October 2007 to help reduce energy and water consumption on campus (Allen 9). The University has implemented these ideas in many of its recent construction projects, and has been both willing and able to reduce its energy demand (Allen 10-4). However, no specific plans have been developed with respect to the university's current cogeneration system. Since the cogeneration system produces 38% of the campus's greenhouse gas emissions (23% from steam and 15% from electric), and purchased electricity comprises another 40% of the total carbon footprint of the university, improvements to the cogeneration system can significantly decrease the university's environmental impact (Tilley 4).

In an effort to meet growing demand sparked by the rapid growth of students seeking on-campus housing, campus expansion is taking place through projects including South Campus Commons Building 7 and Oakland Hall. Consequently, the University of Maryland is investigating the economic viability of a new biofuel cogeneration facility on the north side of campus. Preliminary studies suggest CHP to be an economically viable component of the North Campus expansion despite rising natural gas prices (Orlando 1). The researcher concludes that a new CHP system could produce annual savings of $2.12 million at a capital investment of $4.95 million (Orlando 1). A Level II assessment is underway.

3.0. RESEARCH DESIGN

To most effectively address the proposed research topics, this investigation will be separated into two distinct but interrelated studies. First, a generalized analysis of many large campus combined heat and power (CHP) systems and their operating conditions must be conducted in order to develop a Performance Analysis Database (PAD), which will be used to benchmark the performance of the proposed CHP system. Economic and engineering analyses will be used to develop and optimize the performance of this system. The development of this optimized CHP system model will hereby be referred to as Chapter 1. The second phase of the research, labeled Chapter 2, will focus on the application of the optimized CHP design to the University of Maryland at College Park, developed under the framework of a case study. The Chapter 2 analysis pertaining to UMD will provide validation of how the results obtained by Chapter 1 answer the problems posed in the research question.

3.1. CHAPTER 1

Chapter 1 research, presented chronologically below, is developed under the framework of correlational and historical research designs. This chapter focuses on developing a novel CHP system to meet the energy demands of a generic large university campus with a focus on reducing total carbon output.

3.1.1. Historical and Political Analysis

Investigation into the political and technological development of cogeneration systems will provide the foundation for Chapter 1 research. Pertinent examples of federal legislation concerning greenhouse gas emissions, district heating systems, and various energy technologies will be catalogued and used to qualitatively assess the feasibility of proposed energy systems. The research will consider legislation such as the United States Energy Policy Act of 2005, which provides incentives for the development of innovative technologies that reduce greenhouse gas emissions, and Maryland's Carbon Emissions Reduction Act of 2009 which mandates that the state reduce its total carbon output 25 percent by 2020 (Energy Policy Act of 2005; Maryland).

These technological strides will be compiled into a timeline that delimits the capabilities of current combined heat and power equipment and justifies proposals for further research. The synthesis of this information will help the researchers to understand the logistical issues that influence energy infrastructure development, investigate technical issues surrounding CHP system designs, and direct the research towards a more feasible conclusion.

3.1.2. Developing the PAD

Performance of the cogeneration system conceived by the researchers in this study will be established using computer simulations and compared against real performance data of functioning university cogeneration systems. Researchers will survey plant managers via email from universities nationwide that are successfully operating combined-cycle cogeneration plants that burn natural gas. The sample will include all universities listed on the Combined Heat and Power Installation Database, maintained by the U.S. Department of Energy and Energy and Environmental Analysis, Inc (Combined Heat and Power Installation Database). From the universities that respond, data will be collected on the operating conditions, including relevant temperatures, pressures, and flow rates. The complete list of requested data points is displayed in Appendix 3.

Two problems can be easily identified with this approach. The data is subject to a clear response bias, as only the universities that respond will be tallied. Additionally, the data provided may not be complete, rendering some information useless. However, a sufficient variety and quantity of responses should ensure that the data is representative of the current state of CHP performance at large schools. Also, turbine efficiencies, required heat addition, and fuel use are dependent on ambient temperature, and the researchers cannot guarantee that data collected will represent system performance on days with equal environmental conditions. However, various corrections made to the modeling procedures (discussed in section 3.1.3) should account for these differences.

The collected performance data will be compiled into a Performance Analysis Database (PAD), from which the best realized cogeneration performance numbers will be extracted. Expected performance categories include turbine efficiency, percentage of heat production utilized, and overall fuel efficiency.

3.1.3. Computer Modeling

Drawing on technical research and knowledge related to CHP system design, the team will utilize GSP (the thermodynamic modeling software described in section 2.4.) to simulate the performance of the proposed system. This research will extend beyond the commercially available designs for existing CHP systems. An optimized design will be explored with the primary aim of creating a CHP system capable of efficiently meeting the projected loads of a large university campus. The model will be subsequently altered to fit the specific demands of UMD in Chapter 2.

Data gathered from various university CHP systems will be processed with GSP to generate information about the thermodynamic and economic performance of various system designs (Hudson 3). Computer simulations will allow the team to create an optimized but generalized design based upon economic costs, carbon emissions, and thermodynamic efficiency. Given a certain set of parameters defining the demand, duty cycle, climate, and other considerations affecting turbine performance, a method will be outlined to determine the optimal type and configuration of a gas or steam turbine in a CHP system. Computer models can assess the effectiveness of various system components in a variety of configurations given loads. This model will enable the accomplishment of two objectives: determining the viability of implementing different systems in a given area, and evaluating the thermal efficiency or carbon output of each individual system. Evaluation of the validity of these computer models can be achieved by comparing the performance data generated to the actual performance of the Maryland CHP system. This will be achieved by simulating the Maryland system in the software and modifying the software parameters so that the computer output mirrors the real world measured performance characteristics.

3.1.4. Thermo-Economic Analysis

A correlational study will be employed to construct the thermodynamic and economic cost-benefit analysis of the developed CHP designs. A series of formulae (derived from the aforementioned thermodynamic modeling software and selected economic calculations) will be used to evaluate trends in steam and electricity production as they relate to certain independent variables discussed in Section 3.1.2, justifying the use of a correlational study (Leedy 180). Power generation options will be analyzed by their economic viability and capacity to reduce carbon emissions.

The economic analysis will specifically focus on quantifying the monetary value of reduced carbon emissions in relation to energy costs for large university campuses. A baseline for relative quantification of the carbon emissions and economic efficiency of different systems can then be established by examining the performance of existing CHP technologies. In industrial power production, methods that best minimize carbon emissions are photovoltaic, nuclear, hydroelectric, and geothermal power (Bull 1). These methods, however, are some of the most expensive forms of energy generation. The most economical power generation options include gas turbines, reciprocating engines, and coal-fired boilers ("Assumptions" 1; Sims 1319). At the same time, these methods produce comparatively large amounts of carbon. Quantifying the acceptable increased energy costs associated with reduced carbon emissions is essential to the cost-benefit analysis and will affect the economic merits of recommended CHP designs. Results of the study will also prove useful when marketing any proposed design to university officials.

Optimization of economic costs will be based upon balancing the capital investment and operational costs of the systems investigated. Capital costs account for building and land use, as well as the initial investment required to purchase equipment. Operational costs include fuel costs, maintenance (labor and parts), and the established cost of carbon. Thermo-economic optimization will be based on a larger number of variables such as fuel energy density, demand, equipment specifications, and peripheral system components such as reheat, intercooling, and recuperation technologies – each of which impact overall system cost and efficiency. Specifying the exact balance and relative weight of these variables to determine the "optimal" system will require consultation of existing literature regarding CHP systems, a large portion of which focuses upon developing algorithms for thermo-economic optimization.

3.2. Chapter 2

Following Chapter 1, Chapter 2 will be developed in the form of a case study and apply the findings of the first chapter to the energy systems of the University of Maryland.

3.2.1. Historical and Political Analysis

Investigation into the policies and history relating to the University of Maryland's CHP system will provide a foundation for Chapter 2 research. Knowledge of the state of Maryland's and Prince George's County laws regarding energy production, in addition to university campus policy and UMD President Mote's Climate Action Plan, are of great importance when tailoring a CHP system to UMD. Historical research into the procurement of UMD's current on-campus power plant will elucidate details regarding the process by which a state-owned university can expand its energy infrastructure. While the scope of this research will not extend beyond the implementation of modern CHP technologies, it constitutes historical research by exploring why the technology developed as it did and why the University of Maryland chose the specific configuration of its current power plant (Leedy 161).

3.2.2. UMD Case Study

Data providing a firm understanding of the current utility consumption demands and production levels at UMD is critical to the development of a successful case study. Integrated into the utility systems of every building within the UMD campus are automated monitoring systems that document consumption of electricity, steam, natural gas, chilled water and hot water on a 15-minute to 1-hour basis. These data are then compiled into the ITRON Enterprise Energy

Management Suite (ITRON), a campus-wide database of regularly updated utility statistics. Data acquired through ITRON represents the highest-quality primary data of UMD utility production and consumption, and is utilized by campus employees for both research purposes and monthly utility payments. The team has been provided full access to ITRON.

Data will be collected on both the energy production and fuel consumption of the campus CHP system. This data will include the physical power and steam production equipment (turbines, heat recovery steam generators, etc.), system reliability, operational and fuel costs, input levels of fuel, and output levels of power and steam. Data concerning campus utility consumption will include annual trends for usage of power, steam, natural gas, and chilled or hot water, and have a degree of accuracy that enables identification of daily, weekly and seasonal variations in these levels. The data can be reviewed through the ITRON database in a variety of forms—including daily/weekly trends and cross-utility comparisons—and then exported via pre-formatted Excel spreadsheets. Information on the capital costs of the CHP facility can be acquired from contacts within Facilities Management and will be used for the cost-benefit analysis. These data will provide a baseline for UMD utility demand estimates (replacing values for a generic large university) that will be entered into computer simulations to develop a novel campus CHP system.

Models of the CHP system will be generated for UMD-specific utility loads and then undergo a cost-benefit analysis. This analysis will reveal statistics that will be crucial in convincing UMD to accept the proposal, such as the payoff period, or the time in which the proposed system will save an amount equivalent to its capital cost. Cost-benefit analysis will also clarify the risks involved in alternative proposals, including keeping the current system as the primary supplier of campus energy. Final results of the UMD CHP system design will be compiled and presented to campus officials and energy managers as a candidate for the future UMD power plant.

During the development of a proposed power system for the University of Maryland, researchers will work in tandem with school administrators and facilities managers. The Climate Action Plan Workgroup has committed to investigating the possibility of implementing a bio-fuel CHP facility on the north side of campus to meet increasing demand and decrease carbon output (Hannam). The Maryland Environmental Service is already investigating the viability of biomass as a feedstock (considering local availability and energy density) and the possibility of constructing a biomass plant to meet campus requirements (Resource Professionals Group). The Department's research will be taken into consideration when considering fuel types for the optimized system. Also in consideration is the possibility that UMD might decommission its current plant in favor of a cleaner, more efficient option. Total retirement and reconstruction costs will be explored, as well as the payback of a new, larger facility and the possibility of phasing in and out operation of the new and old plants.

4.0. Limitations

4.1. Benefits

The broad scope of this research greatly contributes to its legitimacy. While most CHP systems are designed with a specific user in mind, this research will incorporate data from a broad range of universities. The two-chapter organization of the study provides the advantage of freedom from localized concerns (fuel source, physical construction logistics, etc.) in the first chapter's general model, while maintaining a consideration of UMD's real world demands in the second chapter. Additionally, there are very few analyses that focus specifically on reducing carbon emissions, giving this study a particular academic niche.

4.2. Confounding Variables

There are several confounding variables that may hinder the research. While the university has expressed interest in constructing a new CHP plant, any decision to the contrary may cause this research to lose part of its relevance. It should be noted that policy decisions made by the university have affected research efforts in the past (Hannam). Also, newly developed methods for energy production could provide new alternatives for addressing the research problem, decreasing the applicability of the proposed study's results. Likewise, changes in federal energy policy and campus construction standards could have a similar effect.

The other predominate confounding variables are sources of error in the ITRON data that could skew the results of the data analysis. This could be a result of human error, faulty machinery, or inaccuracy in the methods of data collection. There are many other potential sources of error in the data to be collected. Unseen variations in the University data, assumptions made by the computer modeling software, and approximations made in the thermodynamic analysis are all potential sources of error.

4.3. Drawbacks

The proposed research incorporates several disparate approaches and will require a large amount of data and analysis to reconcile the findings. Collection of too much data, however, will expand the project to an unmanageable scope and obstruct any valuable interpretation or model created. To address this challenge, two distinct foci of the analysis have been identified, each with a dedicated subgroup: one to address the technical aspects of designing an optimal CHP system; the other to consider the economical and political aspects of campus energy systems. An additional challenge of the study is that qualitative aspects of the analysis (government policy restrictions, etc.) will be somewhat subjective and difficult to integrate with the study's quantitative components.

5.0. CONCLUSION

This research is designed to produce a CHP system that will minimize carbon emissions for UMD and other comparable institutions. Through supply and demand analyses of electricity, steam, and chilled water needs characteristic of a typical large university, this research will likely uncover disparities between existing and optimum conditions. This reality provides an opportunity for the conclusions to be applicable to other institutions.

The primary product to be created by this research is a generalizable process that large universities can emulate to develop a CHP system to meet their specific energy requirements. Since the development and implementation of a new energy system is inherently expensive, especially for large campuses, it is important that the design be economically viable. However, to address the research question, the design must also be environmentally sound.

It is understood that such a cost, regardless of the system's merits, will inevitably be considerable. Although an attempt to better meet the university's energy needs by improving the existing CHP system is a great investment from a long-term perspective, the immediate reality is that it requires significant capital expenditure. The ideal system will be economically achievable in the short term, and economically and environmentally advantageous given a certain payback period.

Analysis of a wide range of campus systems will give particular insight into common trends. The research may be augmented by the creation of a standard list of fundamental issues that most universities encounter during the process of producing their own power. One potential example of this type of commonality would be that universities see a substantial drop in power demand during the winter and summer semesters, when most students leave the campus. Items included in such a list will play a major role in the development of the design.

Ultimately, the proposed research seeks to develop a model with important information concerning CHP system design. The particular audience for this model would be institutions in a campus setting that are looking to install a CHP system (UMD included). Most energy companies choose to withhold this information in order to have a stake in the developmental processes when designing CHP systems for clients. As a result, publicly available models and standardized design guides are not as comprehensive or useful as they could be, and do not address issues specific to college campuses. However, the creation of a generalized and comprehensive system design guide is feasible and its existence would be extremely useful to those who are attempting to install a CHP plant (Carr).

The information provided would specifically be targeted towards universities looking to improve their energy systems by reducing carbon emissions and increasing energy efficiency. The guide would take the form of an explanation of both the technical and economic aspects of the CHP technologies that would best fit an institution's particular needs, along with a comprehensive description of the relevant regulations that will affect the implementation process. While the use of this guide would directly benefit the specific universities looking to improve their energy practices, it also addresses global issues concerning carbon emissions and the limited availability of non-renewable fuels.

The case study of the University of Maryland's energy situation would result in a campus-specific guide of recommendations for the College Park campus' needs. The addition of a new residence hall to North Campus and the possible construction of a new power plant are factors that will both influence and be targeted by the suggestions in the guide, which will be updated to match the University's construction plans. Most importantly, the university's goal of reaching carbon neutrality by 2050 will be the driving force behind the importance and relevance of the information created by this research.

Ultimately, by addressing the global energy crisis in a smaller but meaningful context, this research can provide the information and the impetus necessary to stimulate widespread change in energy policy.

Appendix 1: Project Timeline

Spring 2009
- Identify and contact universities of interest
- Begin to generate GUP
- Research potential CHP optimization methods
- Begin designing optimized CHP plant
- Research legislation and technological history
- Select modeling software

Fall 2009
- Colloquium
- Finalize CHP system design
- Run modeling simulations
- Make technical improvements to system
- Begin economic analysis of system
- Complete all background research

Spring 2010
- Undergraduate Research Day
- Continue modeling simulations
- Apply findings to UMD
- Complete economic analysis of GUP and UMD design
- Draft first sections of thesis

Fall 2010
- Draft remainder of thesis
- Edit thesis
- Meet with experts and review findings

Spring 2011
- Complete and submit thesis
- Present findings

Appendix 2: Budget of Projected Expenses

The majority of the funds will be allocated towards obtaining thermodynamic modeling software, which has an estimated cost of $1,500 for a multi-year license. It is hoped that the team will be able to gain permission from groups that already have access to this software, however the assumption that this software will be readily available cannot be made. In addition, the team is planning to travel to power plants in close proximity to the University of Maryland in order to better understand their processes. These trips will incur basic fuel costs, however it is hoped that the actual tours will not present any cost to the team. Remaining costs are small, and result from printing and other minor miscellaneous expenses.

APPENDIX 3: PAD DATA INQUIRY VARIABLES

Cogen System Variables

General System Design					
Fuel Type					
Fuel Energy Density					
	Present (Y/N)	Manfacturer	Model #	Quantity	Efficiency
Compressor (Gas / Steam / Other)					
Multi-Stage (1)					
Multi-Stage (2)					
Intercooler					
Combustor (Gas / Other)					
Boiler (Steam)					
Turbine (Gas / Steam / Other)					
Multi-Stage (1)					
Multi-Stage (2)					
Reheater (Duct Burners)					
Recuperator (Heat Exchange)					
HRSG (Heat-Recovery Steam Generator)					
Boiler (Back-Up Steam Generator)					
Alternate System Peripherals					
Absorption Chillers					
Duct Burners					
System Operating Conditions					
	Single-Stage	Multi-Stage (1)	Multi-Stage (2)		
Ambient $T_{Dry\ Bulb}$					
Ambient $T_{Wet\ Bulb}$					
Air Flow Rate					
Fuel/Air Ratio					
T_{Air} (After Compressor)					
P_{Air} (After Compressor)					
T_{Air} (After Intercooler)					
P_{Air} (After Intercooler)					
T_{Air} (After Combustor)					
P_{Air} (After Combustor)					
T_{Air} (After Turbine)					
P_{Air} (After Turbine)					
T_{Air} (After Reheater/Duct Burner)					
P_{Air} (After Reheater/Duct Burner)					
T_{Air} (After HRSG)					
P_{Air} (After HRSG)					
Fuel Usage					
Fuel/Air Ratio					
Fuel Firing Rate (Combustor)					
Fuel Firing Rate (Reheater/Duct Burner)					
Turbine Output					
Turbine RPM					
Generator Output					
Nominal Power Output (MW)					
Average Power Output (MW)					
Peak Power Output (MW)					
Generator Eff					
Generator Voltage					
Transformer Voltage					
HRSG Input / Output					
Feedwater Temperature					
Steam Production Rate					
T_{Steam} (Produced)					
P_{Steam} (Produced)					
Steam Recovery Rate (%)					
T_{Steam} (Return)					
P_{Steam} (Return)					
Quality (Return)					

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