

## ABSTRACT

Title of Document: ANALYSIS OF A TRIGENERATION  
SYSTEM THROUGH TRANSIENT  
SIMULATIONS

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This thesis develops a transient computer model of a trigeneration system using TRNSYS software. This simulation model can accurately reproduce the results from a real world experiment of a trigeneration system conducted over five days. This model is then applied to an entire cooling season to show the primary energy usage of a trigeneration system using an adsorption chiller to meet the cooling load. These results can then be compared to the primary energy usage of a residence with a traditional grid-powered Vapor Compression System (VCS) air conditioner. In order to evaluate the geographic feasibility of this trigeneration system, four different cities were selected for analysis. The chosen cities had various climate conditions to aid in comparison. An analysis was performed on the primary energy usage, environmental impact, and economic cost of the trigeneration system to demonstrate the feasibility and likely implementation of one form of trigeneration technology.

ANALYSIS OF A TRIGENERATION SYSTEM THROUGH TRANSIENT  
SIMULATIONS

By

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## Dedication

This thesis is dedicated to my wife. She always has supporting words of encouragement.

## Acknowledgements

I would like to thank my wife for her support in all my endeavors. Also, the many members of CEEE at the University of Maryland deserve my thanks for their guidance and support throughout this research.

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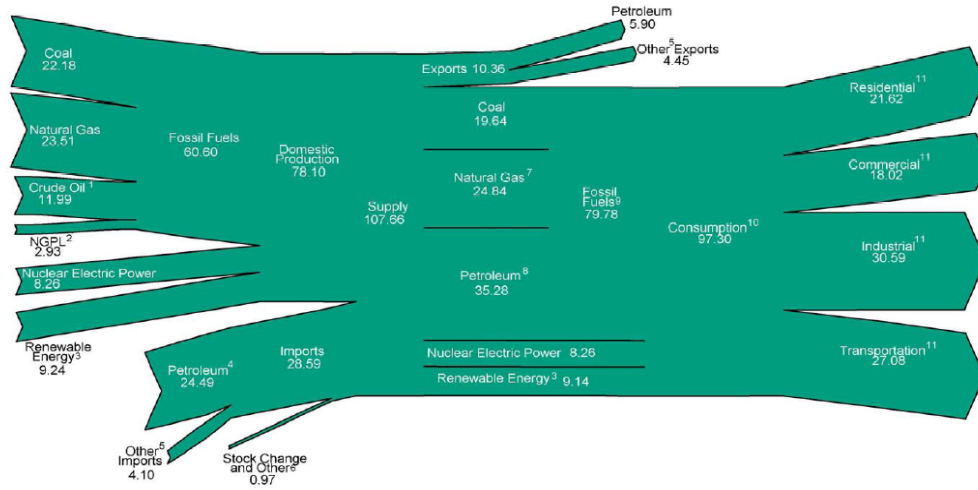
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## Chapter 1: Introduction

An area of research that is gaining considerable mainstream attention within our society is energy. Energy provides the ability to achieve our high standard of living desired by all. However, the current fuels utilized to provide this energy are not infinite. Also, harmful byproducts are produced when this energy is converted from its natural form into useful purposes. Thus, considerable research is being conducted to increase the efficiency of energy systems that will enable reduced consumption of primary fuels and harmful byproducts.

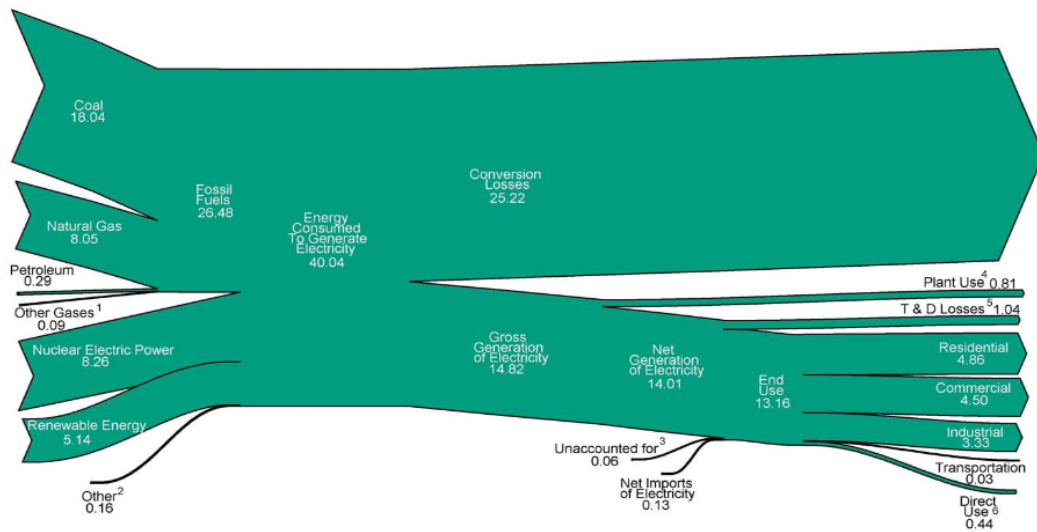
In 2011, the United States consumed 97.30 quadrillion British Thermal Units (BTUs) of energy split between the residential, commercial, industrial, and transportation sectors as shown in Figure 1. Of the 97.30 quadrillion BTUs consumed in the US, 40.04 quadrillion BTUs were consumed to make electricity to meet the demands of the four sectors. This is 41.1% of the entire energy consumption.

When investigating further, the electricity flow can be broken down into its constituent parts, as show in Figure 2. Approximately 63% of the energy used to generate electricity is wasted through losses associated with the generation, transmission, and distribution of electricity to the environment.



<sup>1</sup> Includes lease condensate.  
<sup>2</sup> Natural gas plant liquids.  
<sup>3</sup> Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.  
<sup>4</sup> Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.  
<sup>5</sup> Natural gas, coal, coal coke, biofuels, and electricity.  
<sup>6</sup> Adjustments, losses, and unaccounted for.  
<sup>7</sup> Natural gas only, excludes supplemental gaseous fuels.  
<sup>8</sup> Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.  
<sup>9</sup> Includes 0.01 quadrillion Btu of coal coke net imports.  
<sup>10</sup> Includes 0.13 quadrillion Btu of electricity net imports.  
<sup>11</sup> Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.  
 Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.  
 Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

Figure 1: U.S. Total Energy Flow in Quadrillion BTU, 2011



<sup>1</sup> Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.  
<sup>2</sup> Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).  
<sup>3</sup> Data collection frame differences and nonsampling error. Derived for the diagram by subtracting the "T & D Losses" estimate from "T & D Losses and Unaccounted for" derived from Table 8.1.  
<sup>4</sup> Electric energy used in the operation of power plants.  
<sup>5</sup> Transmission and distribution losses (electricity losses that occur between the point of generation and delivery to the customer) are estimated as 7 percent of gross generation.  
<sup>6</sup> Use of electricity that is 1) self-generated, 2) produced by either the same entity that consumes the power or an affiliate, and 3) used in direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment. Direct use is exclusive of station use.  
 Notes: • Data are preliminary. • See Note, "Electrical System Energy Losses," at the end of Section 2. • Net generation of electricity includes pumped storage facility production minus energy used for pumping. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.  
 Sources: Tables 8.1, 8.4a, 8.9, A6 (column 7), and U.S. Energy Information Administration, Form EIA-923, "Power Plant Operations Report."

Figure 2: Electricity Flow in Quadrillion BTU, 2011

There are many reasons for these losses. The centralized power plants that generate this electricity are usually located away from population centers, increasing transmission and distribution losses. These plants consume coal, natural gas, oil, and nuclear fuel to produce the electricity. The national average of plant electrical efficiency of these plants is 35.0% in 2011 (U.S. Energy Information Administration, 2013). In addition, electricity is partially lost through transmissions lines to the end users in the various sectors. Typical transmission and distribution losses account for 7% of the generated electricity (US Energy Information Administration, 2012). These losses do not include the efficiency of the end use device, which adds further energy losses in the system. In the case of an incandescent light bulb, the overall efficiency of the system is less than one percent.

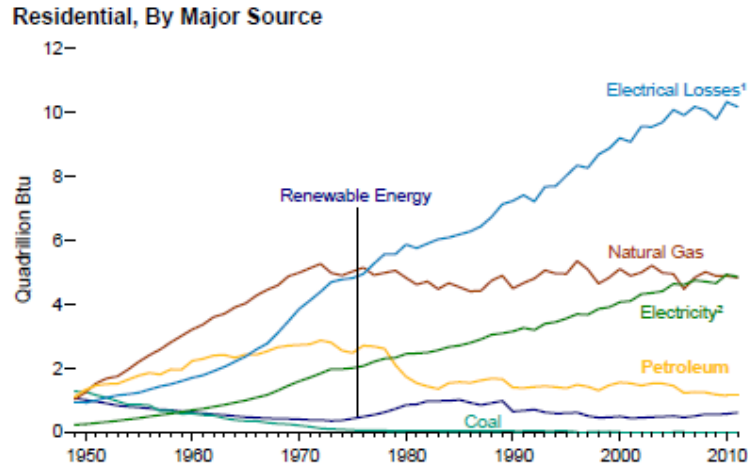
In order for the centralized power plants to generate electricity at high efficiencies, high temperatures are required from converting the primary fuels. Once the high temperature fluid transfer medium is used, the rest is discarded to the environment. This constitutes a major portion of the losses at the central electricity generating plants.

In an attempt to reduce the wasted energy at the power plant and the electrical losses in transporting electricity to individual points of use, combined heating and power (CHP) plants have been developed. CHP plants utilize one form of prime mover, usually an internal combustion engine, gas turbine, or fuel cell. The prime mover will generate electricity and the waste heat from the prime mover is captured. The

electricity is used to power electrical loads at the site, or, if connected, supplied back to the grid. The captured waste heat is then utilized for various processes such as providing hot water, space heating, or manufacturing process. The waste heat can be stored in a thermal storage system and these reserves are utilized when needed.

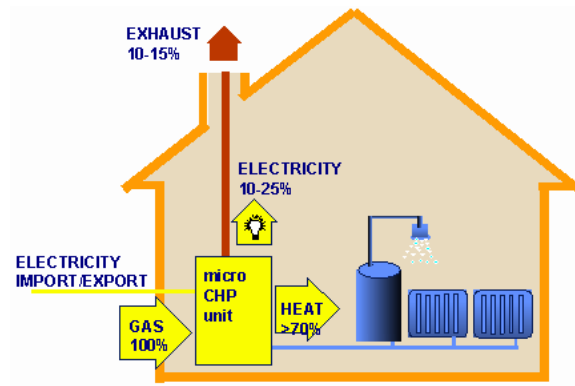
CHP plants were first applied to the industrial sector. This is due to industrial plants requiring a constant thermal load year round, usually in the form of a manufacturing process. That makes these CHP plants much more efficient since the waste heat is utilized by the industrial plant and the electricity is used to offset electrical usage onsite. As technology, policy, and implementation issues improved, CHP plants were then applied to the commercial sector, which included hospitals, office buildings, and universities. One such example is the CHP plant located at the University of Maryland located in College Park, Maryland. With the success of these systems, research was further conducted on applying CHP systems to the residential sector, which could be referred to as micro-CHP.

The residential sector accounts for 22.2% of the primary energy usage and 38.2% of the electricity usage in the United States. As shown in Figure 3, the electricity losses account for 47.2% of the energy used in that sector. CHP plants could reduce this loss dramatically. Today, CHP plants account for 7% of the total electric generating capacity in the United States (US Energy Information Administration, 2012).



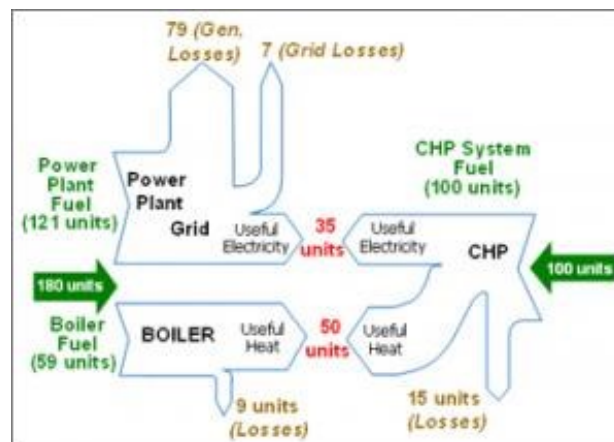
**Figure 3: Residential Uses of Primary Energy**

The CHP systems for the residential sector are modular, but follow the same principles discussed above. The modularity allows for making region and site specific systems that are tailored to the weather and geographical conditions of the location. If the system will be located in an area that receives high annual solar radiation, then PV and solar thermal panels would be a useful addition to the system. If inexpensive natural gas were available directly to the location, then a prime mover that utilizes natural gas would be ideal. An example of a household CHP plant is shown in Figure 4 (Harrison, 2012). Many current prime movers use natural gas as the fuel. With reducing natural gas cost due to the recent resurgence in natural gas production in the US, the payback period for one of these systems will be even shorter.



**Figure 4: Household CHP Diagram**

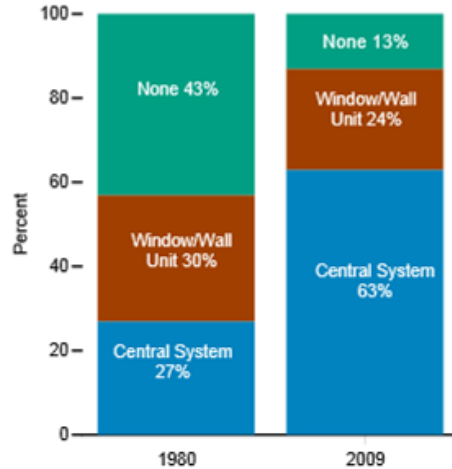
The chart below (Figure 5) illustrates the importance of CHP systems graphically with a Sankey diagram. In this Sankey diagram from the Department of Energy (DOE) (Baker, 2009), the central power plant has an efficiency of 31% and grid losses of 6%. The boiler has an efficiency of 85%. These are typical efficiencies of their devices. The illustrated CHP system has an electrical efficiency of 35% and a thermal efficiency of 50%. To provide the required 35 units of electricity and 50 units of heat, the traditional grid based system requires 180 units of primary energy whereas the CHP system only requires 100 units of primary energy.



**Figure 5: CHP Advantage**

An extension of the CHP methodology is combined cooling, heating, and power (CCHP) systems. This technology would provide cooling to the business/home through different technologies, such as absorption or adsorption chillers. These cooling technologies are thermally activated, meaning they would operate on the waste heat output of the prime mover. These provide alternatives to the vapor compression systems (VCS) that require electricity input to power a compressor to generate the needed cooling. As shown in Figure 6, this could provide valuable savings since 63% of homes are powered by central air conditioning systems, which usually consist of VCS, by using the thermal output of the prime mover during the cooling season. During the cooling season, the prime mover would have to be operated to generate electricity almost entirely to support the electric VCS and the other hot water loads (such as domestic hot water (DHW)) would not be nearly enough to optimally utilize the waste heat from the prime mover. This would cause the system to operate at a lower efficiency, thus increasing its payback period. By understanding the site-specific requirements the CHP or CCHP system would need to meet, the parts of the system can be changed to meet this demand. This is very important when considering the sizing of the various components.





**Figure 6: Air-conditioning System Type**

Another aspect with which to view the advantages of CCHP versus CHP are the heating/cooling degree days of the country. The nominal cooling degree days (65°F base) from 1970-2000 is 1,216. The nominal heating degree days (65°F base) from 1970-2000 is 4,524. That shows that 21.2% of the year the average US household will need to provide cooling to their home (US Energy Information Administration, 2012).

As will be discussed later, the location of the establishment that is utilizing the CHP system matters. This affects whether it is ideal to have a CHP system or a CCHP system, what the prime mover type should be, and the size of the individual components of the system. In addition, the cost of electricity directly affects the payback period. This will be discussed in the economic analysis chapter along with the environmental benefits of such systems.

## Chapter 2: Literature Review

### 2.1 Micro-polygeneration

Over the past 20 years, numerous studies have been conducted detailing the benefits of CHP systems. Most of the early studies detail the effort to expand the use of CHP plants into the commercial sector and the technical challenges that must be overcome for integration (Sweetser, 2002).

In 2006, Wu and Wang conducted a thorough review of the state of the art technologies that are part of CHP systems. They also discussed the proliferation of CHP technologies in various countries around the world and challenges faced with implementation (Wu and Wang, 2006).

Many studies have been conducted to verify the economic feasibility of individual CHP systems with equation modeling. Ren et al. (2008) performed a sensitivity study with a mixed integer nonlinear programming model and showed that various parameters significantly affect the economics of CHP systems. One parameter of note is the size of the thermal storage tank. However, few studies have been conducted using actual CHP systems. This is more difficult since CHP plants vary greatly in size and application. More experiments have been done concerning micro-CHP system. It is difficult to extrapolate the results of these experiments to other situations since each experiment is site specific. One study by Bianchi et al. (2012) discussed general guidelines for selecting the correct micro-CHP system for

residential use, including sizing of various components to provide the best economic analysis for the customer.

## 2.2 Economics

Research has been conducted into helping consumers decide which load applications make the most economic sense to apply CHP technology. One such study was conducted by the United States CHP Association (USCHPA). They detailed that the most efficient and economic CHP operation is achieved when the following three conditions are met. The first is that the prime mover operates near full load for most of the year. The second is that the thermal output of the prime mover (waste heat recovery) can be fully utilized. And the third requirement is that the recovered heat replaces other fuel and electricity purchases that would have been made (ICF International, 2010).

An important consideration is the tax and job issues surrounding the application of CHP plants. While this is mostly beyond the context of the economic study conducted in this paper, they are important considerations. The USCHPA discussed the advantage of increasing the tax credit from 10 to 30% for installed CHP systems. The result would be a 60% increase in the installation of CHP plants. Using a study by Oak Ridge National Laboratory (2008), this tax policy would result in over 23,000 highly skilled jobs based upon four jobs created for every \$1 million in capital investment. This tax policy directly relates to the implementation of CHP systems in the commercial sector.

Industrial buildings already utilize many CHP systems since many require a constant thermal load. But for commercial systems, matching the thermal load with the correctly sized prime mover needs to be considered. Most of the research has been done on utility scale CHP systems and only recently has research been done on micro CHP systems. This is due to the large gain that can be realized by employing CHP systems on sites that use significant amounts of electricity and thermal energy, such as hospitals, schools, and commercial buildings.

Another factor that ties into the amount of hours the prime mover operates each year is the operating strategy utilized. A journal article by Hawkes (2007) provides detailed analysis of operating strategies of different CHPs by studying the least-cost options. Many other site specific factors will ultimately affect the chosen strategy such as net metering policies and year round uses of the generated thermal load.

One factor that will have to be considered is the value of adding cooling to the CHP system. This is especially important in warmer climates where cooling is required for many hours of the year. Thus, the thermal output of the CHP system will need to be utilized during the cooling season in these locations in order to implement a CHP system. There are many thermally activated cooling technologies available and have been summarized by Gluesenkamp and Radermacher (2011) in *Heat Activated Cooling Technologies for Small and Micro CHP Application*. Matching the correct prime mover and cooling technology is vital for success of the system. One such study was

done by Kong et al. (2003), which included simple economic analysis of a Stirling engine with a absorption chiller.

However, the most common prime mover for the residential sector is the internal combustion engine (Wu and Wang, 2006). This is due to their reliability, fast start up capability, and high efficiency at partial load. However, they do have drawbacks such as noise, maintenance, and higher emissions than other options.

### 2.3 Load Following Prime Mover Operation Strategy

Another aspect of the installed CHP system that must be considered is the operating strategy of the prime mover. It can be operated in thermal load following or electric load following. In electric load following, the prime mover operation would be based upon the electrical needs of the site. If electricity were not required, then the system would turn off. For thermal load following control systems, then the prime mover would operate to produce the waste heat required to supply the heating or cooling required. The electricity is then used to power various loads at the site with excess being sold to the grid or additional electricity bought as needed. If storage systems are employed, such as batteries for electrical storage or water tank for thermal energy, then a hybrid control strategy is utilized to achieve the greatest savings. However, according to Zogg and Roth (2005), micro-CHP systems should utilize a thermal load following strategy due to the correct electrical efficiency of micro CHP prime movers. Thus, micro CHP systems are the most economical in colder climates where there is a higher demand for the thermal output of the prime mover (Zogg and Roth, 2005).

## Chapter 3: Objective

### 3.1 Objective

This thesis will use transient simulations in a computer software program to show the potential benefits of an experimental trigeneration system designed for a residential house. This is useful since the computer model can take a small-scale experiment and extrapolate the results to an entire year in multiple locations without having to actually perform the experiments.

There are many reasons why homeowners would want to invest in a CHP or CCHP system. Some of these include individual control over electricity supply to their house and a potential increase in efficiency. As with many product ideas, the only way they become implemented is to have the economics support their purchase.

One reason for installing a home energy system is reliability of electric power. If the system were installed in a home, then it would be independent of the community's electrical system. When storms hit, the homeowner would not have to worry about trees falling on the power lines and knocking out power. These CHP systems are mostly internal to the house.

Another aspect of reliability is the effect that rolling blackouts could have on the reliability of the electricity supply. When the demand for electricity exceeds supply, rolling blackouts can occur where the electricity is turned off for groups of people for

different times of the day. These reliability issues have caused frustrations for many homeowners across the country. The blackouts usually occur during the hottest days of the year, when many people are running their energy intensive air conditioners.

Increased efficiency could also be achieved by installing a CHP or CCHP system at a house. The turbines at large centralized power plants are able to operate at a higher efficiency than smaller machines due to their higher operating temperature.

However, this also means that a larger amount of waste heat generated. This lowers the overall plant efficiency to around 35.0% in 2011 (U.S. Energy Information Administration, 2013). For CHP or CCHP systems, the designed intent is to utilize this waste heat from the prime mover for a useful purpose. This repurposed waste heat would now be utilized to provide space heating in the home during winter, space cooling in the home during the summer, and the domestic hot water (DHW) needs of the building year round. The potential savings are shown in Figure 5 above.

Another factor to be considered is the cost of the installed CHP or CCHP system. While the capital cost of such a system is significant, this may be less of a hindrance to purchase when electricity rates increase. As utility electric rates increase and the price of natural gas or solar panels decrease, these systems may become less expensive for a homeowner to install and utilize. These varied motivations have led to an increase in research into micro-CHP and micro-CCHP systems for the residential sector.

### 3.2 Approach

This thesis work relies upon work done by three previous students for their thesis research. First, Andrew Mueller modeled an existing building in the College Park, Maryland area with TRNSYS, a computer simulation program, for his thesis (Mueller, 2009). Next, John Bush modeled a CHP system in TRNSYS for his thesis (Bush, 2010). Last, Kyle Gluesenkamp built the CHP system that John Bush modeled, and then modified that CHP system into a CCHP system by adding an experimental zeolite adsorption chiller to provide cooling (Gluesenkamp, 2012). He then conducted a five-day experiment using a building load profile generated from Andrew Mueller's TRNSYS file. This thesis expands on these three students work to show the potential benefits of utilizing trigeneration systems during the cooling season across multiple cities.

The first model is developed to simulate the real world performance of the five-day CCHP experiment. This includes correctly accounting for actual loss terms in the system. These results are then compared to the actual results of the experiment to assess the validity of the TRNSYS simulation model. Next, a building load profile is developed from a separate TRNSYS simulation program, initially created by Mueller. Then, the generated building load profile is applied to the CCHP system where actual benefits can be envisioned for the cooling season.

All initial modeling occurred for one location near College Park, Maryland. Once the above results are obtained, then the building is 'moved' to different geographic areas



of the country to analyze which locations are suited for this type of CCHP system based upon a primary energy usage analysis for the cooling season.

The cooling season is defined as when the mean daily temperature exceeds the cooling season human thermal comfort standards two days in a row. The cooling season human thermal comfort standard defined by ASHRAE is 24°C dry bulb temperature (ASHRAE, 2009).

### 3.3 Background

Prior to describing how the experimental CCHP system was developed, an introduction into the basics of CHP systems must be discussed. First, the main component of the system is the prime mover (PM). The prime mover is the integral part of centralized power plants and CHP systems. The design and selection must be specific to the overall stated outcomes required, which is how the centralized power plants and CHP plants differ. The prime mover can be a spark induced internal combustion engine (SI-ICE), Stirling engine, fuel cell, etc. The prime mover would have an electrical output that includes a generator making electricity from the spinning shaft of the prime mover or steam driven turbine. This electricity would be used to power electrical loads within the home. Any unused electricity could then either be sold back to the electric utility company, stored at the home in a device such as a battery, or even supplied to nearby homes. When the prime mover is off, the electrical loads could be supplied by a battery charged from the prime mover or directly from the utility grid. Battery technology is not yet as robust as needed to

withstand the non-uniform charge and discharge cycles that would occur; therefore, most CHP systems buy electricity from the grid when their prime mover is off.

The difference between large centralized power plants and the small scale CHP or CCHP system is that the CHP or CCHP systems capture the waste thermal energy of the prime mover. Usually in large power plants, this is rejected into the environment. Some large plants do conserve this energy, such as the CHP Natural Gas plant in College Park, MD (US DOE Mid-Atlantic Clean Energy Application Center, 2010), but as a rule, it generally is not exploited. This is mostly due to power plants not being located near any major source of industry or homes that can utilize this lower temperature energy. The cost of piping this waste heat to customers near the plant is expensive, making it prohibitive. In addition, a significant portion of the usable energy would be lost in the piping to the environment if it had to travel any distance to the end customer. A common measure of performance of CHP systems is the primary energy ratio (*PER*), as shown in Equation 1.

$$PER = \frac{Q_{clg} + Q_{htg} + Q_{dhw} + P_{elec}}{Q_{fuel}} \quad \text{Equation 1}$$

The *PER* is a ratio of the useful outputs divided by the amount of fuel consumed to produce those outputs. Thus, the greater the value the more advantageous it is.

However, the calculation of *PER* changes for other types of systems and is specific to the types of cooling and heating employed.

A common analogy can be used to describe the wasted heat of the prime mover. A typical car engine can fulfill the prime mover as described above. The energy

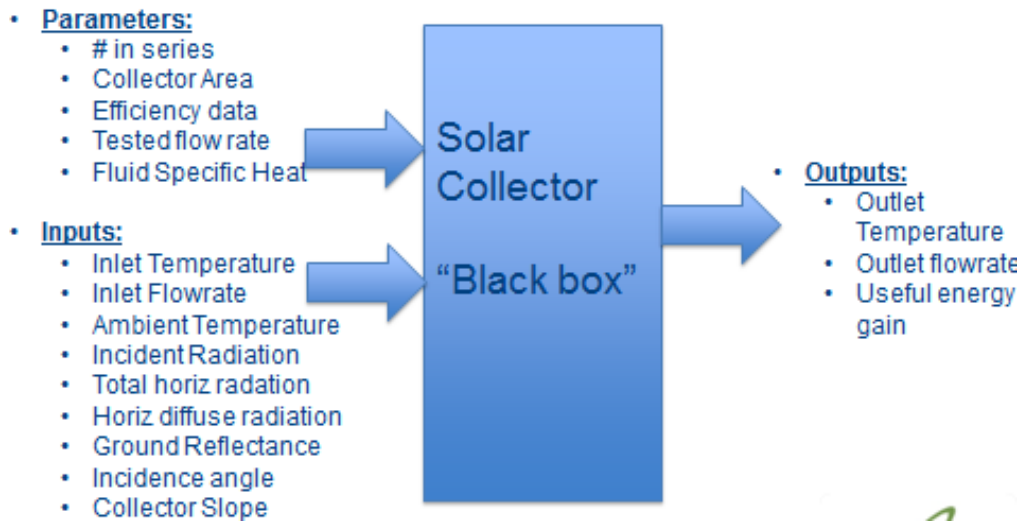
generated by the engine to propel the car forward is synonymous with generating electricity in the CHP system. The left over heat from the combustion process in the car engine is then expelled to various components, including the engine coolant, where it is ultimately expelled to the outside environment. The goal of the CHP system is to capture this energy to provide some useful purpose within the home. By doing this, the efficiency of the CHP cycle will increase and reduce the amount of primary energy required to meet the demand.

### 3.4 Software Platform

TRaNsient SYstem Simulation Program (TRNSYS) was used extensively for the computer simulation work of this thesis (TRNSYS, 2013). Its benefit compared to other energy simulation software products has been previously detailed in a previous University of Maryland CEEE thesis (Lust, 2008). TRNSYS was developed by University of Wisconsin – Madison that was made commercially available in 1970's. It started out as a method of detailing the energy profile of solar panels and has grown to include many other types of component models.

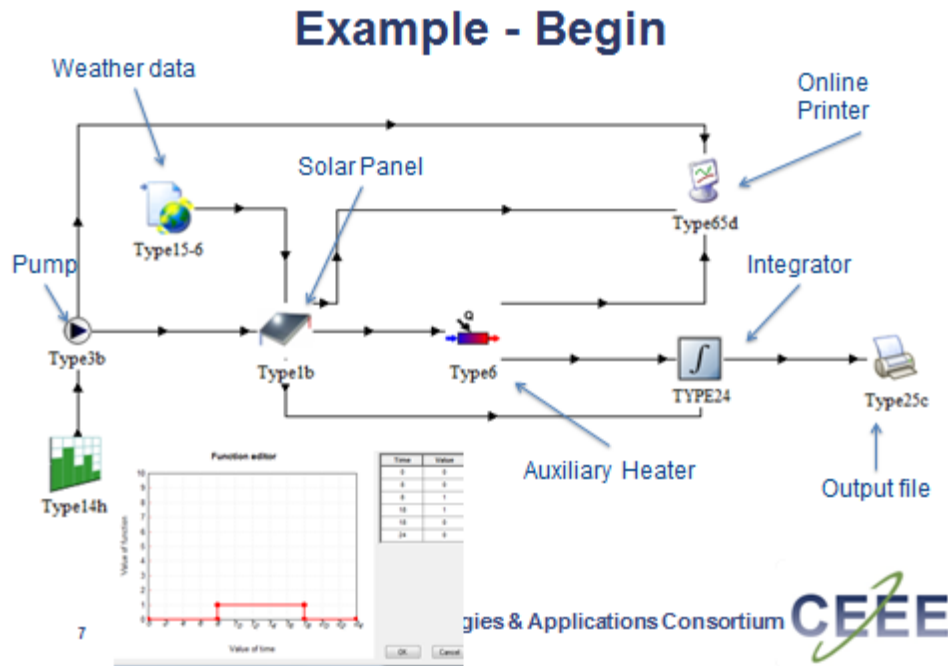
TRNSYS is a modular 'black-box' simulation computer software program with a strong graphical user interface. The outputs of one 'module' are connected to the inputs of another 'module' as needed to obtain the desired response. An example of a solar collector module is shown in Figure 7 below. This allows a complex problem to be broken down into many smaller manageable problems (shown in Figure 8) with intermediate outputs that can be monitored for troubleshooting purposes.

## Solar Collector



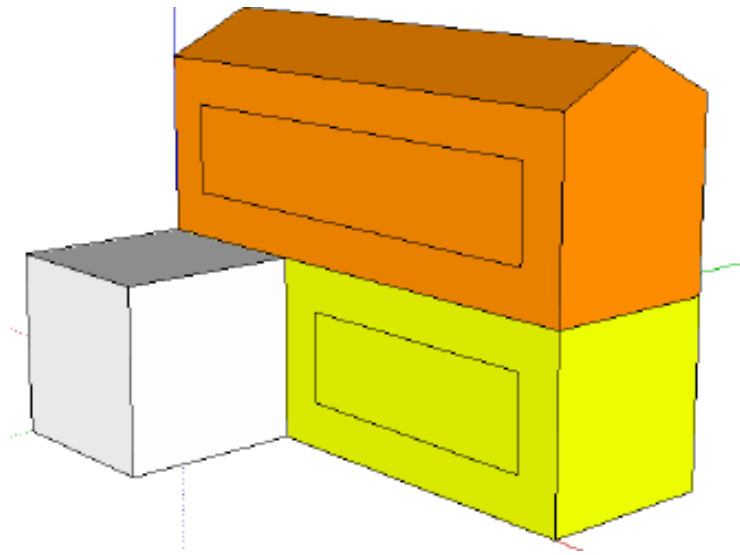
**Figure 7: TRNSYS Module Example**

Each module contains the mathematical equations necessary for each step in the simulation process. Over the years, many ‘modules’ have been created that add to the utility of the software program. The underlying governing equations are written in FORTRAN computer code and are hidden from the user. However, through a subprogram called TRNedit, users can develop their own ‘modules’ as needed, further increasing the usability of the program. Modules also exist that allow interaction with other computer programs such as EES, EXCEL, Matlab, COMIS, and Fluent, to allow ease of data manipulation.



**Figure 8: TRNSYS Simulation Example**

Buildings can be modeled with the TRNBuild application of TRNSYS. Different modeling approaches exist based upon the degree of complexity and accuracy required. A new feature included in TRNSYS 17 is the ability to interact with Google SketchUp where buildings can be viewed in 3D coordinates. In addition, this feature allows for viewing results of the simulation, such as zone temperature, in Google SketchUp, allowing for more detailed illustration of the simulation (TRANSSOLAR, 2012). This is shown in Figure 9 where the different colors correspond to the zone temperature.



**Figure 9: Google SketchUp 3D Drawing**

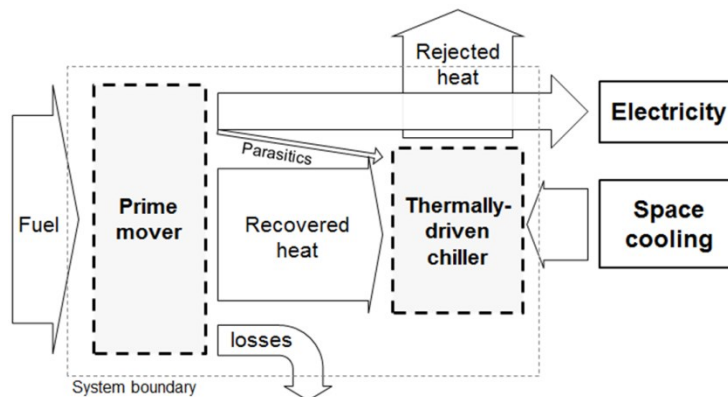
## Chapter 4: Model Development

### 4.1 Experiment Overview

The experimental CCHP system modeled for this thesis was designed and built by Kyle Gluesenkamp in the Center for Environmental Energy Engineering (CEEE) at the University of Maryland located in College Park, Maryland. Major components of the system include the prime mover, adsorption chiller, and thermal storage tank (Figure 10). Tests were conducted over many years to allow for development of various aspects of the system. The last was an entire test of the CCHP system for a five-day period simulating the cooling season at a typical home in College Park, Maryland. The results of this five-day test were used as the basis for validation of the modeling simulation. This CCHP system, as shown in Figure 11 below, was able to provide cooling, domestic hot water, and space heating from the recovered thermal output of the prime mover and electricity from the generator of the prime mover.



**Figure 10: Experiment Setup**



**Figure 11: CCHP System**

This micro CCHP system was designed to be utilized by small office buildings or large residential homes. Historically these systems have been designed for larger commercial uses. However, as described above, there is new research into applying this technology to smaller buildings to reduce the primary energy demand of the U.S. residential sector.

#### 4.1.1 Prime Mover

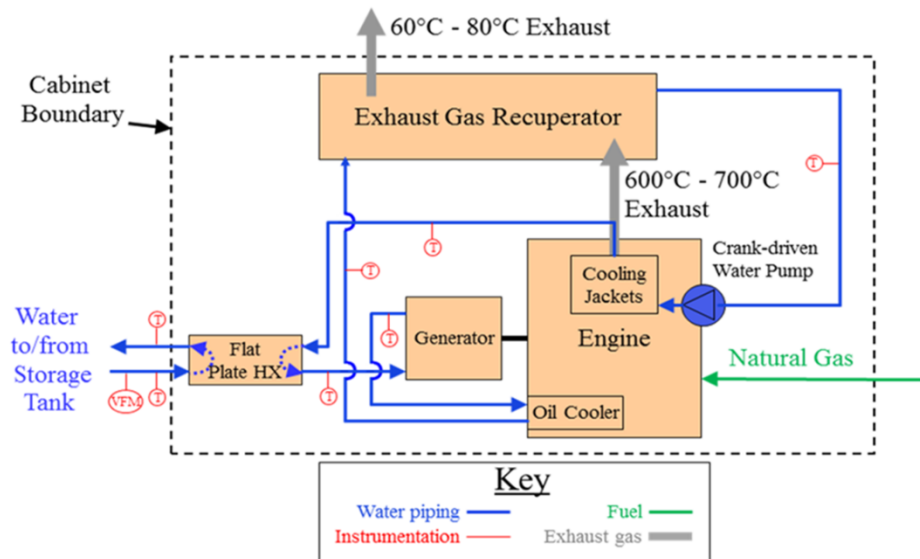
A Spark Ignition Internal Combustion Engine (SI-ICE) was used as the prime mover. The unit selected was a 4 kW<sub>e</sub> Marathon Ecopower engine. The engine and all of its components are contained in a single cabinet. Natural gas supplied from the local utility was used as the fuel source. The exhaust gas was piped to the outdoor environment. Intake air into the combustion chamber was taken directly from the laboratory ambient air. A control strategy was provided in the software purchased with the prime mover, but was not utilized during the five-day test. The process used will be described in a later section.





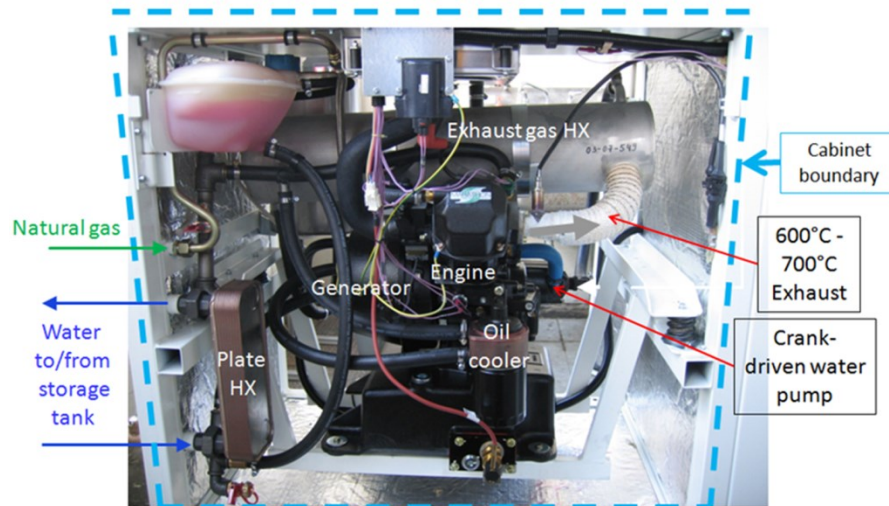
**Figure 12: Experiment Setup**

Within the PM cabinet, the thermal energy is captured by the engine coolant loop. Instead of radiator coolant that most would typically use in a car engine coolant loop, water is utilized. It is circulated through the oil cooler jackets, cooling water jackets, and exhaust gas recuperator. Then the water circulates through a plate heat exchanger where the thermal energy is transferred to a second water loop as shown in Figure 13.



**Figure 13: Diagram of Waste Heat Recovery in Ecopower Engine**

This water is then supplied to the top of the thermal storage water tank. By utilizing a second loop, the temperature of the water returning to the prime mover was controlled. This is accomplished with a diverting valve in the secondary water loop that controls the return water temperature, which is identified as M1 in Figure 16. The majority of the recovered thermal energy in the prime mover is recovered by the exhaust gas recuperator plate heat exchanger. The exhaust gas exits the combustion chamber of the prime mover at 600-700°C and leaves the plate heat exchanger at 60-80°C.



**Figure 14: Inside of Ecopower Cabinet**

#### 4.1.2 Thermal Storage Tank

The 220-gallon tank is used to store the thermal energy generated by the prime mover. The tank is maintained stratified in temperature, which means the hottest water is at the top. This is due to needing water at different temperatures to enable running the cooling process in the adsorption chiller. Hot water at approximately 70°C enters the top of the tank from the prime mover. Return water back to the plate

heat exchanger of the prime mover leaves at the bottom of the tank. Water leaves the tank at the top to supply hot water to the space-heating loop to heat the house and for the domestic hot water required for consumption within the house. Make up water to compensate for the domestic hot water load is supplied at the bottom of the tank and is at the city tap water temperature. The return water for the space heating loop also returns at the bottom of the tank. Water for the adsorption chiller is supplied from the top of the tank and returns to the middle of the tank. The water supplied to the adsorption chiller is the reason for requiring the tank to remain stratified.

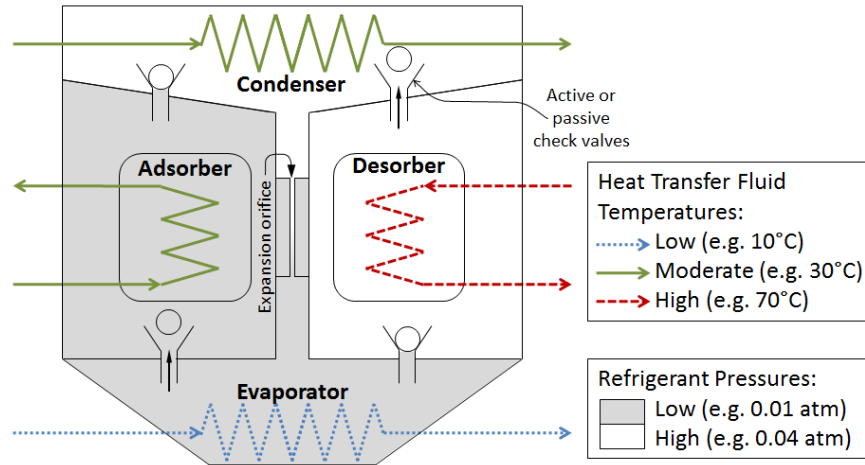
#### 4.1.3 Heating

The heat from the CHP system is usually supplied by radiant heating through pipes throughout the house. When needed, a pump in the space heating loop would energize that would send water through the pipes in the house from the top of the hot water storage tank. Heating would either be in the form of floor radiant heating or radiators. The space heating function of the CHP system was not utilized for the five-day test since its objective was to provide cooling at a typical College Park, Maryland residence in July.

#### 4.1.4 Cooling

The chosen method of cooling was with an adsorption chiller (Figure 15). This was chosen, as it was able to provide the necessary cooling with the relatively low temperature energy recovered from the prime mover. The designed chiller has two sealed adsorption chambers. Within each sealed chamber is a coated heat exchanger with internal piping that allows the heat transfer fluid to enter. The coating can often

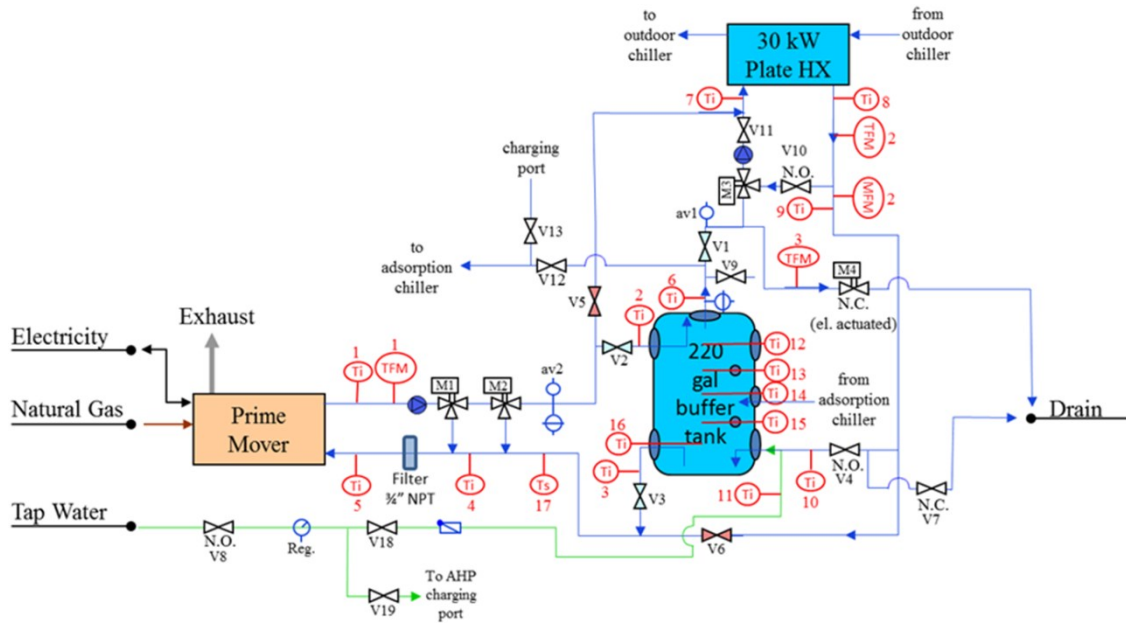
be some proprietary form of zeolite. The refrigerant within the system is the only vapor phase fluid, which is water in this experiment. When the cycle is in operation, one chamber is heated with water from the top of the thermal storage tank (heat transfer fluid) while the other chamber is cooled with ambient temperature fluid. The hot temperature water causes the refrigerant (water) to desorb from the coating of the heat exchanger. Eventually the pressure in the desorber chamber increases above the pressure to activate the check valve at the top of the chamber. Then, the vapor enters the condenser and condenses by ambient temperature water flowing through the condenser heat exchanger. The resulting liquid then flows down by gravity through an expansion device, adiabatically cooling in the process. This chilled water then cools the output chilled water of the adsorption chiller in the evaporator. This causes some of the refrigerant to evaporate, which would normally cause the pressure to increase in the evaporator. However, the refrigerant vapor is adsorbed by the adsorption bed in the adsorption chamber due to the cooler heat transfer fluid circulating through the second coated heat exchanger. This process continues until all the refrigerant is desorbed from the first chamber and adsorbed by the second chamber. Then, the process is reversed by switching which sealed chamber the hot heat transfer fluid from the thermal storage tank is supplied to.



**Figure 15: Basic Adsorption Chiller Cycle**

#### 4.2 Trigeneration System Model

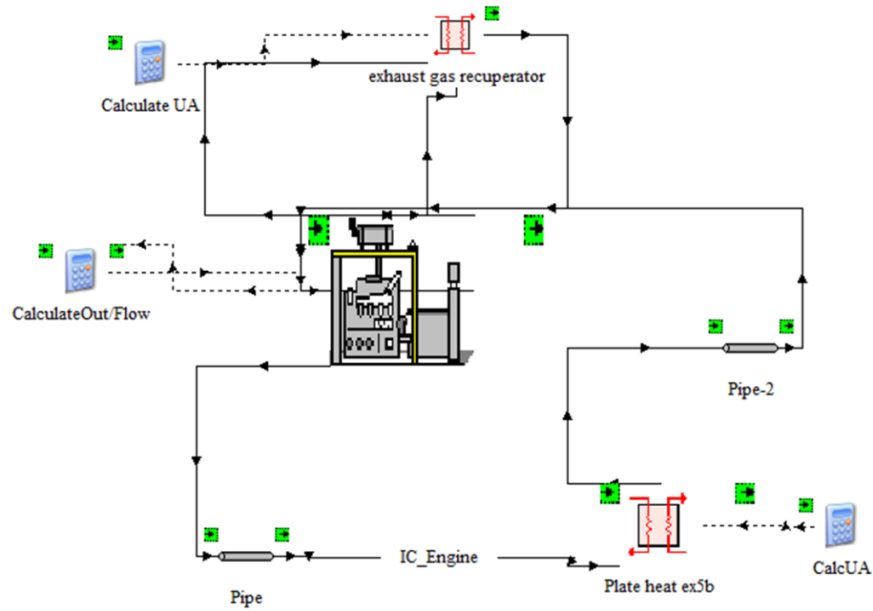
In Bush's work (Bush, 2010), the experimental CHP system was modeled. It utilized the Ecopower engine as the prime mover with the thermal output providing space heating and domestic hot water from the thermal storage tank. His model was then updated to match the CCHP results from Gluesenkamp's experimental work. This was done by adding the performance map of the experimental adsorption chiller, and updating the performance map of the Ecopower engine and updating the various loss coefficients of the interconnecting pipes and thermal storage tank. Once the base model was verified against the results of the five-day experiment, additional updates were implemented that would more accurately simulate the trigeneration system over the course of the cooling season in multiple locations.



**Figure 16: Diagram of Experiment Setup**

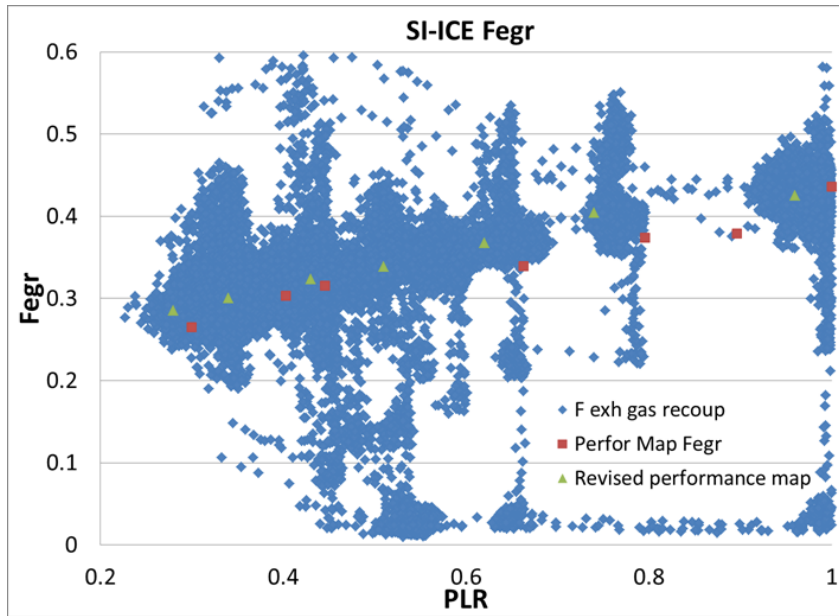
#### 4.2.1 Prime Mover Model

The prime mover schematic is shown below in Figure 17. The engine coolant cycles through the oil cooler, cooling water jackets of the engine, and the exhaust gas recuperator prior to transferring its heat through the plate heat exchanger to the stratified storage tank.

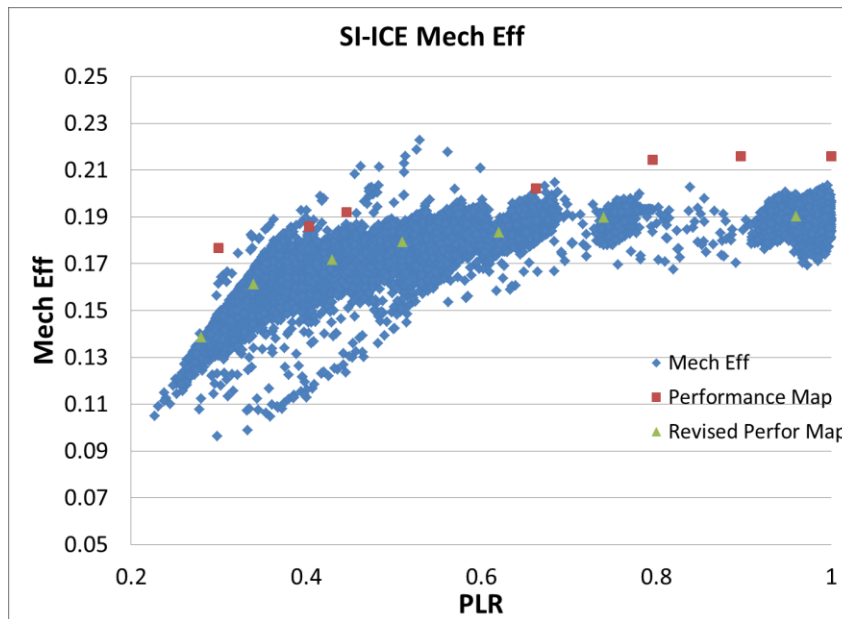


**Figure 17: Model of Prime Mover**

The prime mover utilizes a user supplied performance map to correctly allocate the fuel usage to various components. To generate this performance map, the results of the five-day test were used. The values were averaged over a small range of Part Load Ratio (PLR) points to accommodate the fluctuations in the measurement of the PLR. The PLR of the prime mover was calculated based upon the maximum electrical output of the prime mover generator of 4 kWe. The graphs below (Figure 18 and Figure 19) show the results of the five-day test (blue dots). The green dots are the averaged data points used in the new performance map for the prime mover. The red dots are the results of a previously generated performance map for comparison purposes.



**Figure 18: Prime Mover Coefficient – Exhaust Gas Recup**



**Figure 19: Prime Mover Coefficient – Mechanical Efficiency**

The heat transfer coefficients of the exhaust gas recuperator and plate heat exchanger to the thermal storage tank were also required to be calculated in the same manner as above. A trend line was generated with the PLR as the input and these equations

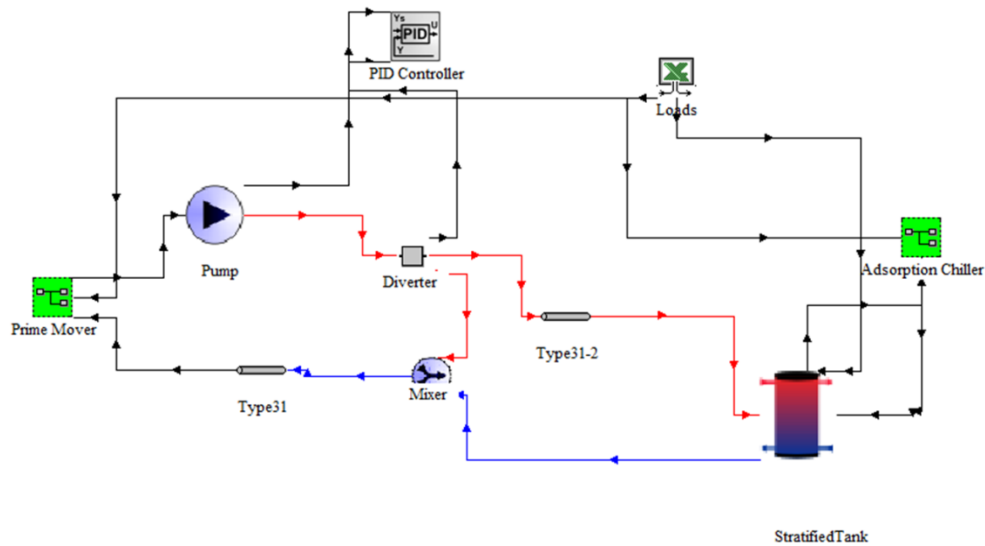


were utilized within the modeling program to calculate the UA value of each heat exchanger.

The performance map indicates that the overall efficiency of the prime mover has decreased over the past two years. The red dots represent the old performance map of the Ecopower engine that was developed in 2010 by Bush. The green triangles represent the new performance map of the prime mover based upon the five-day experiment. This discrepancy is believed to be due to required maintenance needing to be performed on the engine, such as changing the oil and air filter, which was conducted soon after the experiment was complete.

#### 4.2.2 Thermal Storage Tank Model

The next section of the model, shown below (Figure 20), details the process of transferring the heat from the prime mover plate heat exchanger to the thermal storage tank. Water leaves the heat exchanger and travels through a pump that provides the required flow. The pump only operates when the PM is operating. The water then flows through a mixing valve. The PID controlled mixing valve controls the return temperature to the prime mover heat exchanger to ensure that adequate cooling is provided. The remaining water then flows into the top of the tank.

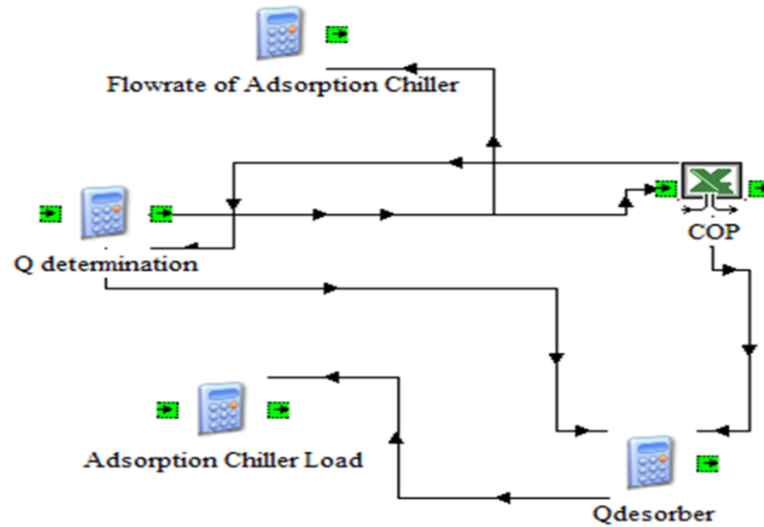


**Figure 20: Model Overview**

The tank in Figure 20 is modeled with 39 temperature nodes. A more detailed analysis of the modeling of the tank is provided in Bush’s thesis (Bush, 2010). Therefore, only differences will be discussed in detail here. Hot water for the domestic hot water load and adsorption chiller was supplied from the top of the tank, as in the experimental setup. The space heating aspect was not modeled, but could be implemented quickly to handle the heating season. The return water from the adsorption chiller returns to the middle of the tank. Makeup tap water to compensate for the water lost to the domestic hot water loads is supplied to the bottom of the tank.

#### 4.2.3 Adsorption Chiller Model

The last major section of the model is the adsorption chiller (Figure 21). Since TRNSYS is not equipped with a model of an adsorption chiller that correctly modeled experimental setup, one was integrated into the model with equations, data call routines, and a performance map.



**Figure 21: Adsorption Chiller Model**

Based upon initial experimental results of the adsorption chiller, a performance map was developed. This then allowed for development of a control strategy for the operation of the adsorption chiller. This is needed to specify the length of time that the adsorption chiller would operate in one direction before reversing direction in order to continue to provide cooling. The control strategy also calculated the heat recovery time. By allowing the ‘hot’ heat transfer fluid from the desorption bed to heat the cooler metal of the opposite adsorption bed during the switching process, energy can be saved instead of acting as a load on the next cycle. The control strategy was developed by Gluesenkamp and aspects of it were utilized in the TRNSYS model to compute the COP of the chiller and the load of the chiller on the thermal storage tank.

During the five-day test, a valve in the heat recovery section of the adsorption chiller was inadvertently shut causing a reduction in capacity and COP of the chiller. This

was correctly implemented in the simulation by generating a performance map of the chiller that did not include performance metrics from heat recovery. This led to a believed COP reduction of 5-10%.

### 4.3 Building Model

Since the experiment was conducted in the laboratory and not at an actual residence, a load profile had to be generated to simulate the CCHP system being located in an actual residence. This was generated from TRNSYS modeling work conducted by Mueller. In his work, he modeled an existing house in the College Park, Maryland area and generated the load profile from TMY-2 weather data based in Stirling, Virginia, which is the closest city to College Park, Maryland for which TMY-2 weather data is provided.

#### 4.3.1 Modeled Residence

The modeled home is a 2,500 square foot house located near College Park, Maryland. The house was built in the 1980s so values for materials used for the building simulation were chosen from this time period's building code. Additional details on specific building envelope properties are included in Mueller (Mueller, 2009).

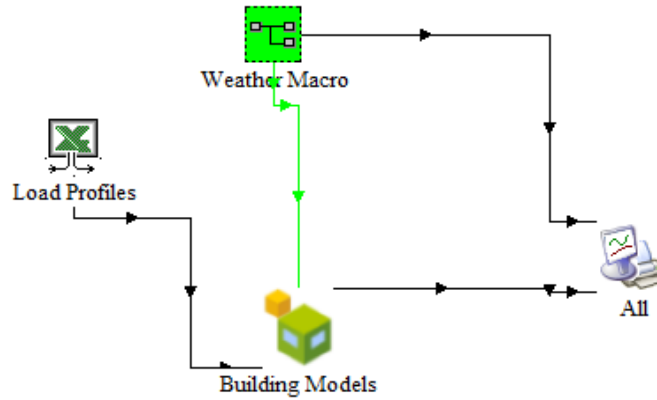
#### 4.3.2 HVAC

The house utilized a 7 kW gas furnace for heating that is 85% efficient. A 7 kW sized unit vapor compression split system was used as the central air conditioner. For domestic hot water, the home used an 80 gallon hot water tank with an electric heater.

### 4.3.3 Simulation Model

Generating the load profile of the building was based upon satisfying the imposed load of the weather upon the physical characteristics of the building to maintain the desired indoor thermal conditions. In the load profile for the five-day experiment, the latent and sensible aspects of the cooling load were separated. The sensible cooling load was met with the adsorption chiller and the latent cooling load would be supplied by a separate electric VCS air conditioner. The VCS air conditioner was not physically implemented, but its energy usage was calculated by an EES programming routine and factored into the total electrical production of the prime mover. This Separate Sensible and Latent Cooling (SSLC) strategy was utilized to allow for higher operational performance of the adsorption chiller. The adsorption chiller would have to supply water at 7°C to meet the entire latent and sensible demand whereas by just supplying the sensible demand, the adsorption chiller supplied water could be 14°C (Gluesenkamp, 2012), and thus had greater operating characteristics.

The below figure, Figure 22 shows a simplified model for generating the building load profile. TRNSYS, through its TRNBuild subprogram, calculates the various loads on the building for each time step. The program does this with the physical properties specified in the building file. This model output the outdoor and indoor temperature and relative humidity along with the sensible cooling and heating demand along with the latent demand. These values were then manipulated to construct the load profile used to determine the cooling load placed on the adsorption chiller during the specified period.

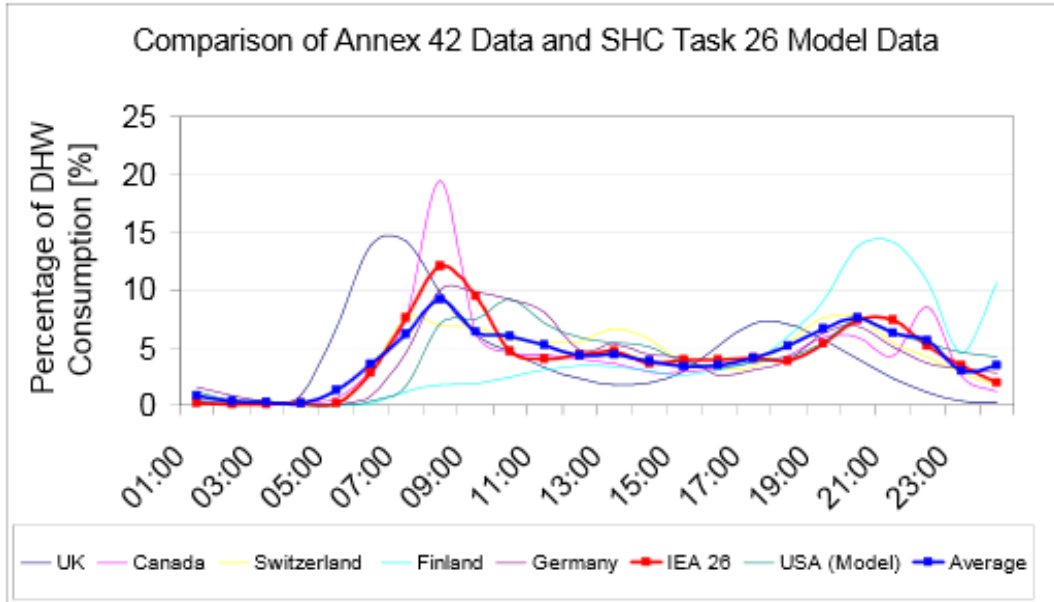


**Figure 22: Model of Building**

#### 4.4 Load Profile

##### 4.4.1 Domestic Hot Water

The Domestic Hot Water profile was obtained from IEA Task 26 (Knight, 2007). The profile chosen is constructed of 5 minute data points. The IEA validated the accuracy of this profile using recent data. The probabilistic data was generated based upon consumption of 300 Liters/day for a single-family house in North America. As can be seen below (Figure 23), the Task 26 profile matches closely with the profiles given by various countries for daily water consumption.



**Figure 23: Comparison of Annex 42 DHW Profile with the SHC Task 26 DHW Profiles**

The profile assumes that the supplied temperature is 45°C with a cold tap water resupply temperature of 10°C. Since this is almost never the case, the profile must be modified based upon the actual temperatures encountered using the equations described below.

$$Actual\ Vol = \frac{35}{Stored\ Water\ Temp - Cold\ Tap\ Water\ Temp} \times Profile\ Vol$$

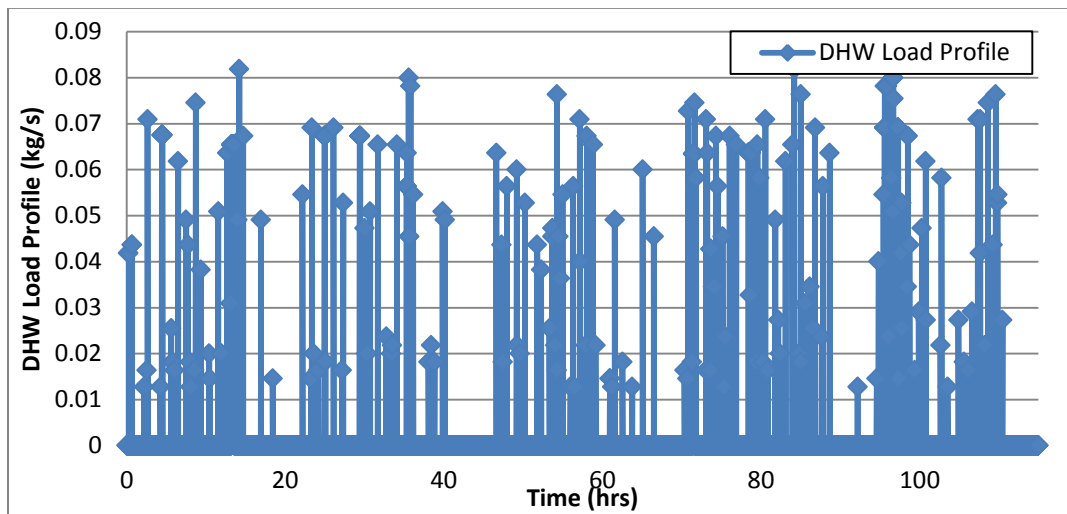
**Equation 2**

In Equation 2, *Actual Volume* refers to the volume of hot water drawn from the storage tank. The *Stored Water Temperature* is the temperature of the water at the top of the thermal storage tank. The *Cold Tap Water Temperature* is the temperature of the local tap water temperature supplied to replace used water from the tank. The *Profile Volume* is the DHW profile data from IEA Task 26. This results in less water

actually being distributed from the storage tank since there is a higher temperature lift in the trigeneration system ( $\sim 50^{\circ}\text{C}$ ) than the IEA Annex 42 profile data ( $35^{\circ}\text{C}$ ).

Of note, the Annex 42 domestic hot water profile does include consumption for clothes washing machines and dishwashers, and takes into consideration the day of the week, season, and holiday variations. The profile was generated based upon consumption in Germany and Switzerland, but as Figure 23 shows, is applicable to many other countries as well.

Since the trigeneration system built in the laboratory has physical limitations required by the flow meter, the profile had to be modified. The total flow per hour was maintained by combining flows below the minimum and flows above the maximum were spread over multiple time steps. The profile for the five-day experiment is shown in Figure 24. These modifications were not included when generating results over the cooling season.



**Figure 24: DHW Profile for Five-day Experiment**



#### 4.4.2 Cooling

As discussed above, the cooling profile was based upon the imposed load on a simulated building located in College Park, Maryland. The building model was then used to generate load profiles for different cities with different weather patterns. This helped assess the range of applicability of the experimental adsorption chiller.

#### 4.4.3 Heating

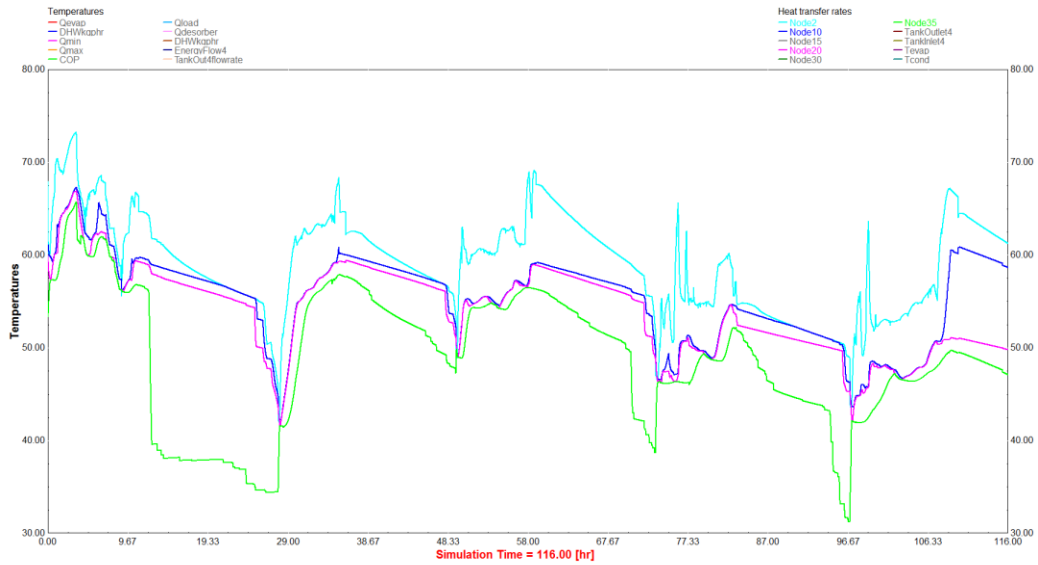
The heating season was not analyzed with the experimental CCHP system. Therefore, to maintain continuity of results, the heating season was not included in the simulation models. All results detailed below are for the cooling season only. The heating season could be easily implemented though. The most difficult portion would be deciding on and implementing a correct load profile. This would then enable the correct amount of hot water energy to be drawn from the tank. Another major consideration would be to decide how to provide the heat required by the load profile. Many options are available and factor into sizing considerations of the specific CHP system site requirements. One option is to provide heat from the thermal storage tank through radiate heated floors or radiators. Another is to provide heat from a furnace (auxiliary boiler) or use the electricity generated by the CHP system to power the compressor of a heat pump system.

## Chapter 5: Model Validation

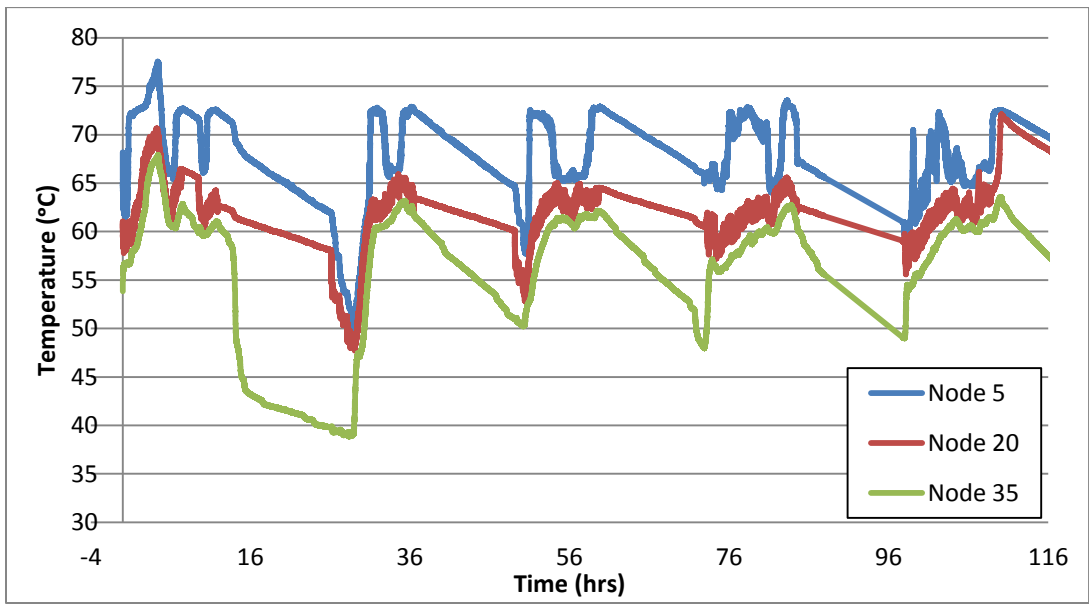
### 5.1 CCHP System Simulation Results

#### 5.1.1 Storage Tank Water Temperature Profile

An important interface between the thermal loads and the thermal energy provided by the prime mover is the buffer storage tank. This is where the buffer capacity is stored to allow the prime mover not to operate the entire day to meet the thermal demands of the building. Due to this relationship, this is an important location to validate the simulation results with the experimental data. Many aspects must be checked to validate the simulation of the storage tank. The temperature stratification within the tank is important in validating the thermodynamic accuracy of the model. This is true for the calculations for the amount of hot water (and thus thermal energy) drawn from the top of the tank for domestic hot water since the load profile is based upon 45°C which is then scaled to 70°C to calculate the correct amount drawn from the top of the tank. If this temperature varies much outside of this temperature range, then the simulation will not be able to be compared to the experimental results. In addition, the adsorption chiller was designed to operate with a hot temperature of 68-72°C going into the desorber bed with a lower temperature at the middle of the stratified tank for the return water. If these are not present, then the performance map generated for the adsorption chiller, with which the COP and thermal energy draw from the tank is calculated, is incorrect. The comparison is detailed in Figure 25 and Figure 26 between the simulation and experimental values.



**Figure 25: Simulation Tank Profile Temperature**



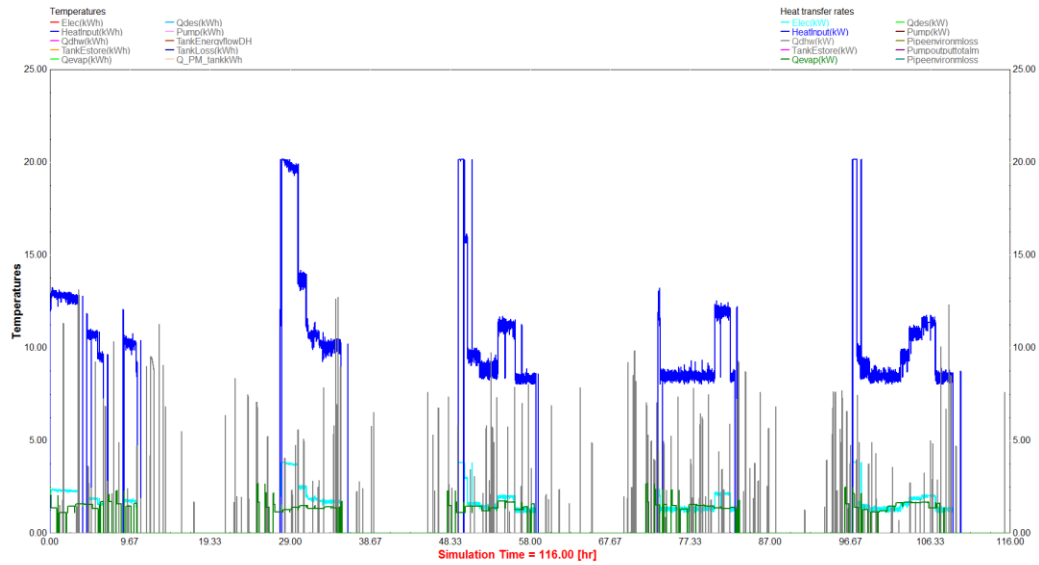
**Figure 26: Experiment Results - Tank Temperature**

The two figures depict the tank temperature at the top (Node 5), middle (Node 20), and bottom (Node 35) of the thermal storage tank. As explained above, the simulation modeled the tank with thirty-nine vertical nodes while the actual temperatures were measured at thirteen vertical locations. The thermocouple temperatures of the experiment were then equated to nodal number to compare them

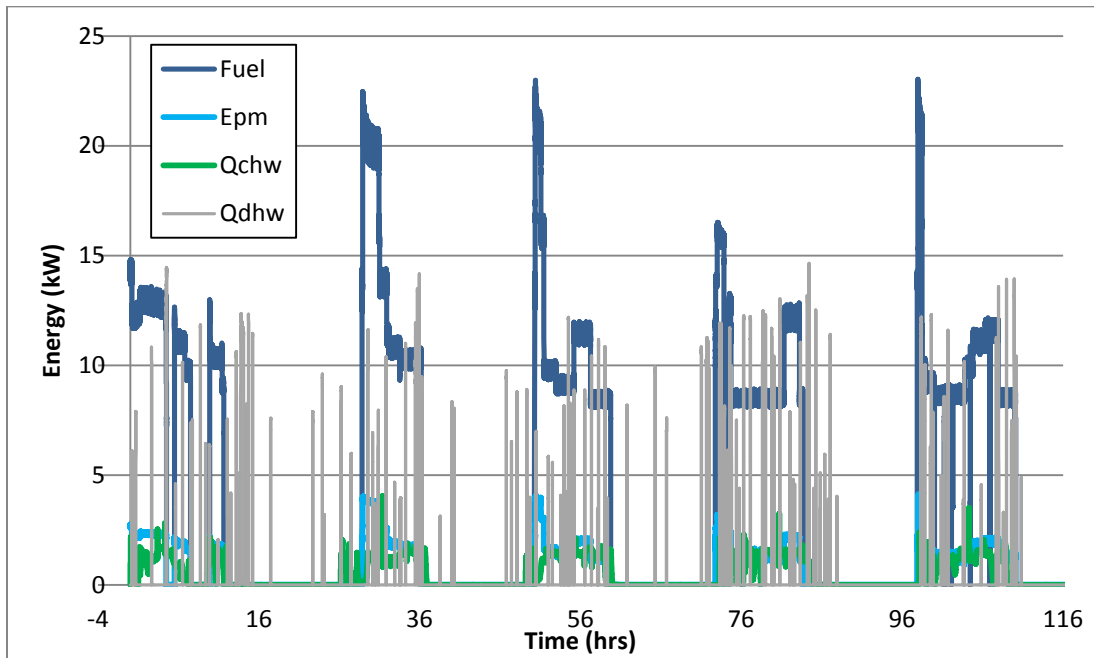
to the simulation results within the storage tank. As stated by Gluesenkamp (2012), there were two periods around hours 27 and 50 where the prime mover was not operating when it should have, which caused the tank temperatures to drop below the required value, hurting the capacity of the system.

As seen in Figure 25, the top of the tank is mostly within the 68-72°C temperature range required for accuracy of the adsorption chiller and domestic hot water load profiles. As expected, the temperature of the tank drops throughout the night based upon thermal losses to the environment and domestic hot water demand. The top of the tank never drops below 45°C, which is the minimum value considered as useful for providing domestic hot water. Increased demand for hot water from the thermal storage tank is expected during daylight hours. This corresponds to more individuals being awake that require domestic hot water for showering, cooking, cleaning, and laundry. In addition, in the summer season, it is the hottest during the day. This causes a higher demand for air conditioning, and thus of thermal energy from the tank to provide this cooling from the adsorption chiller. Thus, as expected, the prime mover must operate to replenish this heat used to meet the loads. This can be seen in the simulation results of Figure 25.

Another important aspect to verify is the instantaneous inputs and outputs of the CCHP system. The input is the fuel required to operate the prime mover and the outputs are the cooling produced, domestic hot water provided, and electricity generated. These are compared in Figure 27 and Figure 28.



**Figure 27: Outputs of CCHP System**



**Figure 28: Outputs of Experimental CCHP System**

As indicated, the inputs and outputs are correctly matched for time of day and amount. This is important as it indicates that the simulation programming was able to correctly respond to the implemented load profile. By correctly accounting for the loss terms, the prime mover fuel output of the simulation is the correct ratio to the

desired load profiles. If the loss terms were incorrect, then more or less fuel would be required to provide the necessary cooling and domestic hot water.

### 5.1.2 Total Energy

In Table 1, the total energy values are compared from the experiment and simulation data. The percentage difference in the last column is comparing the simulation results to the experimental data. Percentages relating to the amount of fuel consumed will be detailed in Table 3.

**Table 1: Results Comparison**

<i>Energy Type</i>	<i>Five-day experiment (kWh)</i>	<i>TRNSYS Model (kWh)</i>	<i>Difference -</i>
Fuel Consumption	517.7	501.8	3.1%
Electricity Production	90.4	87.0	3.8%
Chilled Water Production	61.6	67.6	9.7%
Domestic Hot Water Production	23.8	30.5	28.2%
Tank $E_{store}$	4.38	3.3	-
Desorber Heat Input	177.7	164.0	7.7%
Heat Captured from PM	303.9	296.6	2.4%
Heat Loss from Tank	44.9	39.1	35.2%

### 5.1.3 Discussion of Results

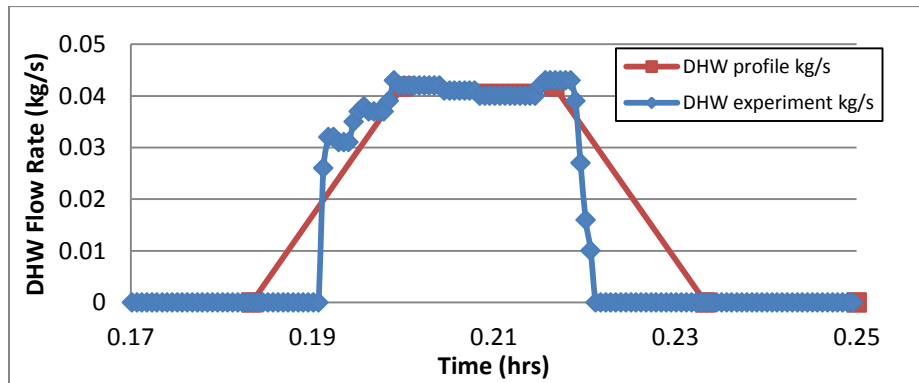
As can be seen in Table 1 above, many of the results are close. Both the fuel required by the prime mover and the electricity generated match closely with the experimental results. In addition, the thermal energy transferred from the prime mover to the

thermal storage tank part of the CCHP system matched closely. However, due to the differences discussed below, many of the other comparisons are not as accurate.

The result with the most error is the domestic hot water. This is due to the solenoid-operating valve not being able match the supplied load profile. An example of this is shown in Figure 29. This resulted in 66.3% less hot water (by mass, kg) being used in the experiment than in the profile. The TRNSYS simulation is based upon the load profile. Once this difference is compared to the energy difference, it reduces the error to within 4% as in the other errors.

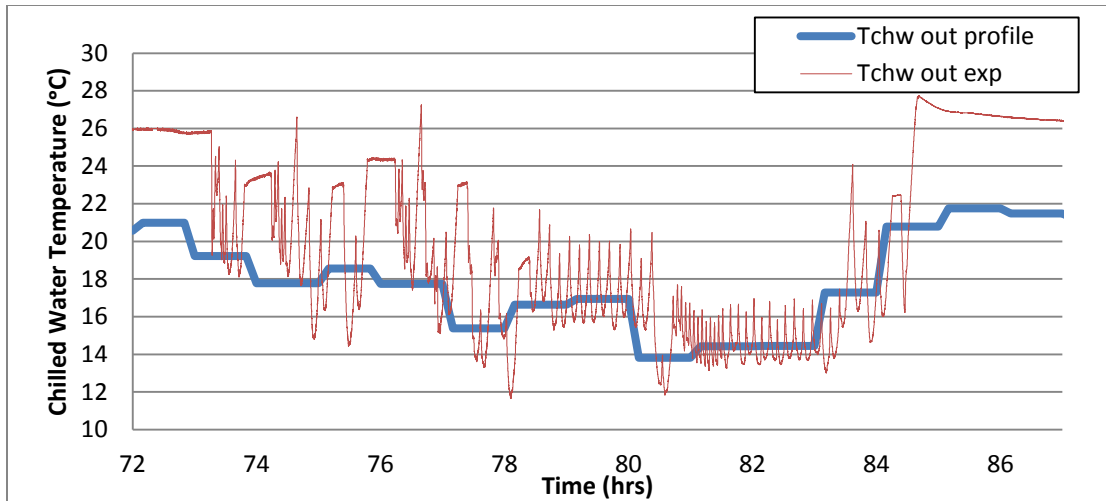
**Table 2: DHW Comparison**

	<i>Experiment</i>	<i>Profile/Simulation</i>	<i>Difference</i>
DHW (kg)	57223.9	86282.0	33.7%
Energy Usage (kWh)	23.8	30.5	35.2%



**Figure 29: DHW Result**

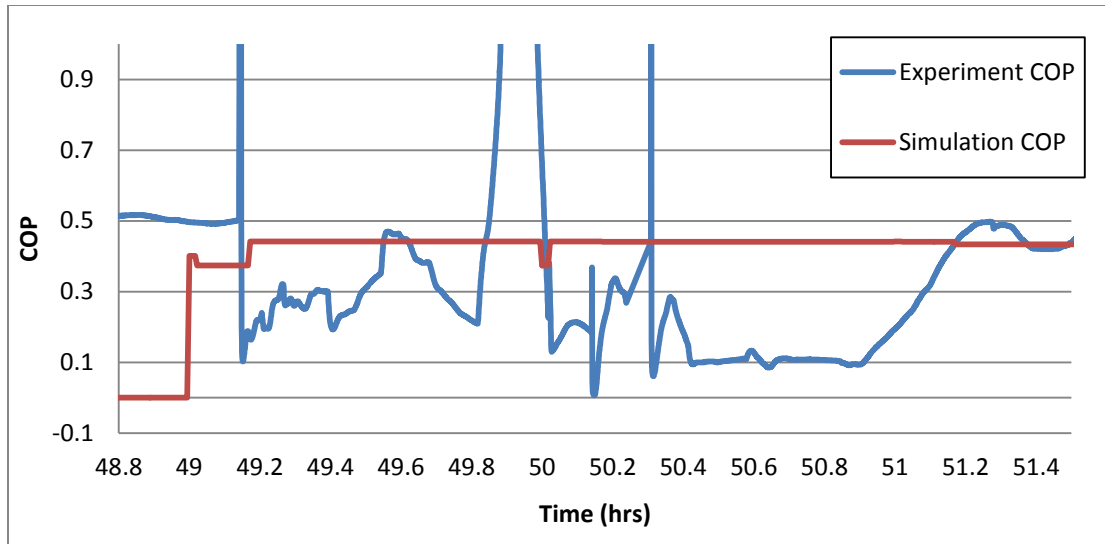
One induced error is the amount of chilled water produced by the adsorption chiller. As discussed by Gluesenkamp (2012), the capacity was less than predicted by the load profile since heat recovery was not operational during the five-day test. It can be seen though, that the chilled water production outlet temperature matches closely when the adsorption chiller is in operation in Figure 30.



**Figure 30: Chilled Water Outlet Temperature**

Another small difference was the amount of thermal energy required from the tank to supply the required cooling through the adsorption chiller. The simulation results required 7.7% less energy than the five-day experiment. This is due to performance degradation associated with the initial start up of the chiller each operational period. When the chiller starts up, some of the initial supplied energy is required to be utilized to heat and cool the respective piping and heat exchangers, lowering the COP. Once the system was running, the experimental system would match the performance map data used by the computer simulation. Using Figure 31, the adsorption chiller is started at hour 49, where the COP is approximately 0.4. But, the experimental adsorption chiller doesn't reach full capacity until hour 51.2.





**Figure 31: COP of Adsorption Chiller**

Next, the results are compared as a ratio of total fuel consumed by the prime mover. This allows a comparison between the experimental and simulation data, with which the percentages can then be compared. The raw data is presented in Table 3. This data has been shown graphically in Figure 32 and Figure 33.

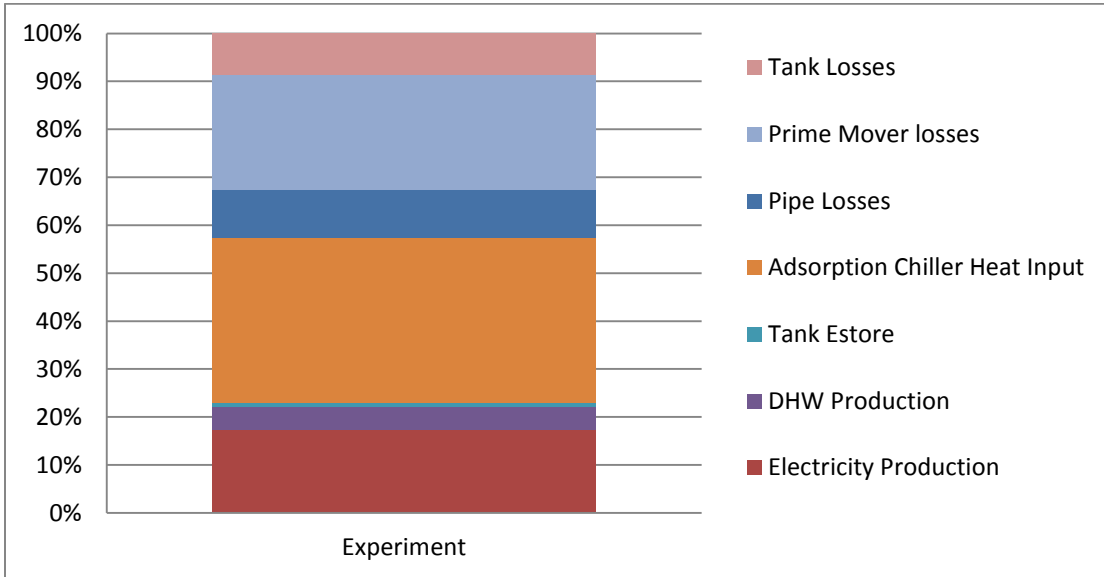
**Table 3: Comparison to PM Input Fuel**

	<i>Experiment</i>		<i>Simulation</i>	
	Value (kWh)	Percentage of Total	Value (kWh)	Percentage of Total
Fuel Consumption	517.7	-	501.8	-
Electricity Production	90.4	17.5%	87.0	17.3%
DHW Production	23.8	4.6%	30.5	6.1%
Tank $E_{store}$	4.38	0.8%	3.3	0.7%
Chiller Heat Input	177.7	34.3%	164.0	32.7%
Pipe Losses	53.1	10.3%	59.7	11.9%
PM Losses	123.4	23.8%	118.2	23.6%
Tank Losses	44.9	8.7%	39.1	7.8%

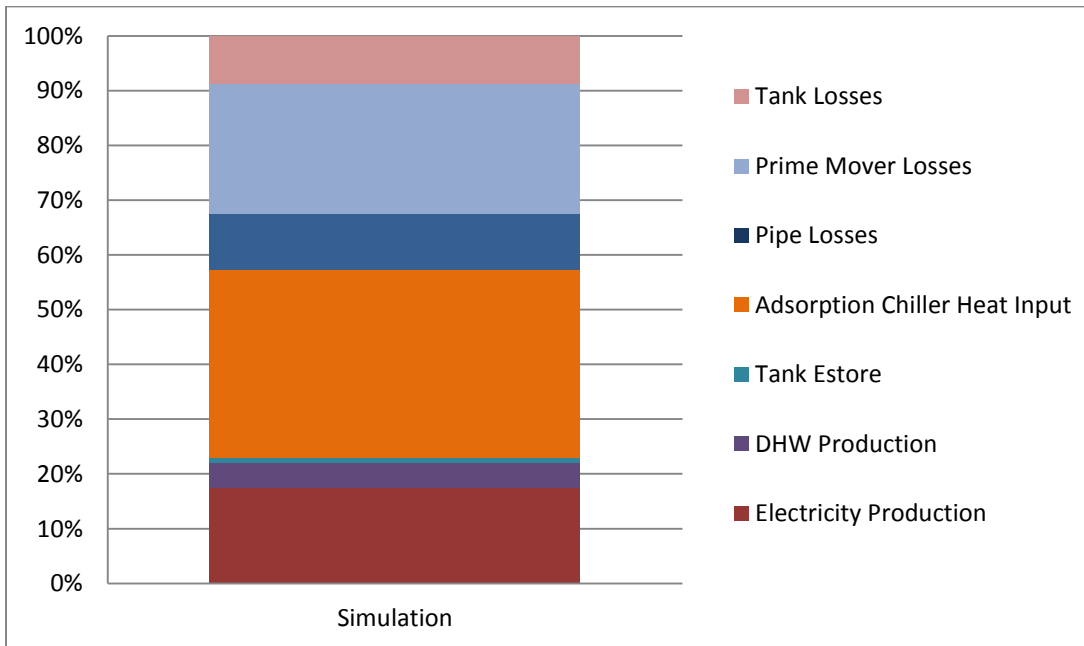
When compared to a ratio of the fuel input into the PM, the percentages are close.

The biggest difference is 1.6% with the amount of domestic hot water production, adsorption chiller heat input, and pipe losses within the system. These percentage

difference are smaller than when compared to the total kWh comparison since they now take into account the relative size of the category in relation to the overall fuel input value of the PM.



**Figure 32: Comparison of PM Input Fuel for Experiment**



**Figure 33: Comparison of PM Input Fuel for Simulation**

As the data shows in Table 3, this gives an efficiency of 57.8% for the experiment, which is lower than expected for the prime mover individually. The prime mover has

an efficiency of 76.2%. This is due to the system not having enough insulation built into the piping system, tank, and adsorption chiller. If this would be included, the resulting efficiency would begin to approach that of the prime mover. It would never fully reach that value however due to some heat losses to the environment never fully able to be removed. Also, some energy would be required to heat or cool the dead mass in the system through temperature fluctuations as it operates.

The simulation resulted in an overall efficiency of 56.7% for the CCHP system, which is less than one percent from the overall efficiency of the experimental CCHP system. Also, the PM had an efficiency of 76.4%, which is within 0.2% of the experimental prime mover.

As the previous comparisons have shown, the simulated CCHP system in TRNSYS closely matches the experimental CCHP system. This computer model will be used as the basis for further analysis of the experimental CCHP system.

### 5.2 Building Load Model

The CCHP system requires a load profile for operation of the adsorption chiller.

From this, the amount of energy withdrawn from the tank for operation of the adsorption chiller is calculated. The building load profile used in the five-day experiment was used in generating the valid CCHP simulation model results.

However, the building load profile has to be recreated in order to extend the results over the cooling season and to multiple geographic locations.

### 5.2.1 Building Model

To verify the validity of the building model, the load profile used in the five-day experiment was recreated. This would ensure that the correct building characteristics were implemented to allow for accurate simulation comparisons.

**Table 4: Load Profile Comparison**

<i>Yearly Total</i>	<i>Experiment Load Profile</i>	<i>Regenerated Load Profile</i>	<i>Difference</i>
Ambient Temperature	105223.2	105223.2	0.0%
Ambient Relative Humidity	619285	619285	0.0%
Indoor Temperature	194877.8	191952.9	0.04%
Indoor Relative Humidity	376326.6	376038.2	0.08%
Sensible Load	21357037	21201212	0.73%
Latent Load	76672.6	77089.4	0.54%
Infiltration	4423.2	4423.2	0.0%

The data in Table 4 was generated by summing the values for each parameter over the entire year. This was done to ensure that the new load profile generated matched closely throughout the entire year and to emphasize any small errors that may not be noticeable on a smaller time scale. As shown, all parameters are within one percent over the course of the year. Therefore, any smaller variations on individual time steps would equal out over the course of the simulation period. In addition, by verifying over an extended time period allows for validation when the simulation is implemented over the course of the cooling season in a location.

### 5.2.2 CCHP System

Using the newly generated load profile, the validated CCHP system model was employed to verify that correct results were still obtained. Also, a control strategy was implemented in the simulation model. During the experimental test, the PM was controlled manually based upon the impending load on the thermal storage tank. The

Ecopower engine does have a control strategy based upon the temperatures within the storage tank, but could not be used as this would cause the entire tank to be at the same temperature whereas the adsorption chiller required a stratified tank. The actual PLR used in the five-day experiment was utilized for the simulation models discussed above. A new control strategy was implemented that mimicked the operation of the PM during the five-day experiment. The results are shown in Table 5 and Table 6.

**Table 5: Comparison of Simulation Results**

<i>Energy Type</i>	<i>Five-day experiment (kWh)</i>	<i>TRNSYS Model with PLR from experiment (from Table 3, kWh)</i>	<i>TRNSYS with developed control strategy (kWh)</i>	<i>TRNSYS with generated load profile and developed control strategy (kWh)</i>
Fuel Consumption	517.7	501.8	535.0	547.2
Electricity Production	90.4	87.0	89.3	90.9
Chilled Water Production	61.6	67.6	67.0	69.4
Domestic Hot Water Production	23.8	30.5	32.8	28.1
Tank $E_{store}$	4.38	3.3	7.4	10.0
Desorber Heat Input	177.7	164.0	162.3	160.3
Heat Captured from PM	303.9	296.6	315.5	322.6
Heat Loss from Tank	44.9	39.1	42.9	51.2

The results in Table 5 express that the values are similar, but additional comparison is needed in order to validate the generated building load profile and implemented control strategy. This was accomplished by comparing the various outputs of the simulation as a percentage of fuel input, as done previously. This would illustrate that the correct ratio of results are obtained. This is shown in Table 6.

**Table 6: Comparison of Simulation Results as a Percentage of Fuel Input**

<i>Energy Type</i>	<i>Experiment</i>		<i>TRNSYS Model with PLR from experiment (from Table 3)</i>		<i>TRNSYS with developed control strategy</i>		<i>TRNSYS with generated load profile and developed control strategy</i>	
	Value (kWh)	Per. of Total	Value (kWh)	Per. of Total	Value (kWh)	Per. of Total	Value (kWh)	Per. of Total
Fuel Consumption	517.7	-	501.8	-	535.0	-	547.2	-
Electricity Production	90.4	17.5%	87.0	17.3%	89.3	16.7%	90.9	16.6%
DHW Production	23.8	4.6%	30.5	6.1%	32.8	6.1%	28.1	5.1%
Tank E <sub>store</sub>	4.38	0.8%	3.3	0.7%	7.4	1.4%	10.0	1.8%
Chiller Heat Input	177.7	34.3%	164.0	32.7%	162.3	30.3%	160.3	29.3%
Pipe Losses	53.1	10.3%	59.7	11.9%	70.1	13.1%	73.0	13.3%
PM Losses	123.4	23.8%	118.2	23.6%	130.2	24.3%	133.7	24.4%
Tank Losses	44.9	8.7%	39.1	7.8%	42.9	8.0%	51.2	9.4%

The differences between the experiment and the simulation results have been discussed in Section 5.1.3 above. The differences between the three simulation models are largely related to the changes implemented in between each result, as expected. While the difference in the generated load profile does cause some variations, the largest change is instituted when a control strategy based upon maintaining a stratified thermal storage tank is implemented. However, the results are similar and validate the use of this model. It can be extended for use over the entire cooling season and other locations, as discussed in the next chapter.

## Chapter 6: Applicability

The overall goal of the residential CCHP system is to save customers money in order to convince them to purchase the systems. Chapter 7 will cover this in detail through a simple economic analysis based upon the experimental setup. However, prior to generating values for use in the analysis, other factors need to be considered, such as the location of the building.

### 6.1 Locations

Four locations were chosen across the United States in order to analyze the applicability of the experimental CCHP system. This will be completed by utilizing the validated simulation model for the CCHP system discussed in Section 5.2.2. The load profiles will be generated from the building simulation file by changing the weather data applied to each simulation. TMY-2 weather data was utilized for all simulation models. Each building load profile was applied only during the cooling season. The cooling season is defined as when the average daily temperature reaches 24°C for two consecutive data, based upon TMY-2 ambient temperature data for each city. ASHRAE human thermal comfort guidelines specify 24°C for cooling. Table 7 details the cooling season information for the four cities chosen for analysis.

Another factor considered when choosing which cities to analyze was the highest ambient temperature during the cooling season. The ambient temperature factors into the condenser water temperature used for the adsorption chiller load profile. The

maximum condenser water temperature is 37°C, which is the highest condenser temperature the experimental adsorption chiller was designed to operate (Gluesenkamp, 2012). Therefore, all cities are required to have less than a maximum ambient temperature of 35°C during the cooling season, based upon TMY-2 weather data in TRNSYS.

**Table 7: Cooling Season Profile Data**

<i>City</i>	<i>Start</i>			<i>Stop</i>			<i>Total Days</i>
	<i>Hour of Year</i>	<i>Month</i>	<i>Day</i>	<i>Hour of Year</i>	<i>Month</i>	<i>Day</i>	
College Park, MD	3576	May	30	5999	September	7	101
Miami, FL	1200	February	20	7751	November	19	273
Minneapolis, MN	3528	May	28	5735	August	27	92
Albuquerque, NM	4056	June	19	5471	August	16	59

The cities were chosen based on having different climate conditions in order for a comparison study. The building’s physical properties were not changed when the simulation was conducted for each city. It is understood that the average house in the Northeast will not match the average house in the Southwest, but changing the building properties would not allow for a useful comparison. All weather data for the various cities was based upon TMY-2 data found in TRNSYS. This will help keep consistent averaged values throughout the results.

### 6.1.1 College Park, MD

This city was chosen since it is the location of the actual building, where the experimental load profile was based, and has a moderate climate. This location has



502 cooling degree days (CDD) based upon 18°C base temperature with the TMY-2 weather data available in TRNSYS. Table 8 lists the CCHP results during the cooling season in Maryland.

**Table 8: Results of College Park Cooling Season**

<i>Energy Type</i>	<i>Value (kWh)</i>	<i>Percentage of Fuel Input</i>	<i>Fraction based upon CDD.</i>
Fuel Consumption	8829.2	-	17.6
Electricity Production	1495.2	16.9%	3.0
Chilled Water Production	933.5	-	1.9
Domestic Hot Water Production	733.9	8.3%	1.5
Tank E <sub>store</sub>	5.1	0.1%	0.0
Desorber Heat Input	2209.8	25.0%	4.4
Heat Captured from PM	5177.1	-	10.3
Pipe Losses	1189.4	13.5%	2.4
PM Losses	2156.9	24.4%	4.3
Tank Losses	1038.9	11.8%	2.1

#### 6.1.2 Miami, FL

Miami is considered to have a warm, humid climate for most of the year. This led to it being chosen as a city to analyze the CCHP system in the cooling season. Miami has 2,098 cooling degree days during the cooling season. However, the temperatures are moderated somewhat due to the Atlantic Ocean when compared to other cities at that latitude. Table 9 lists the CCHP results for Miami's cooling season.

**Table 9: Results of Miami Cooling Season**

<i>Energy Type</i>	<i>Value (kWh)</i>	<i>Percentage of Fuel Input</i>	<i>Fraction based upon CDD.</i>
Fuel Consumption	25327.3	-	12.1
Electricity Production	4279.0	16.9%	2.0
Chilled Water Production	3022.5	-	1.4
Domestic Hot Water Production	1564.8	6.2%	0.7
Tank E <sub>store</sub>	8.7	0.0%	0.0
Desorber Heat Input	7052.3	27.8%	3.4
Heat Captured from PM	14872.8	-	7.1
Pipe Losses	3413.1	13.5%	1.6
PM Losses	6175.5	24.4%	2.9
Tank Losses	2833.9	11.2%	1.4

### 6.1.3 Minneapolis, MN

This city is considered to have a cold climate year round, with the exception of a short period in the summer. Cooler cities could have been chosen, but they would not have had a lengthy enough cooling season for useful comparisons. This led to it being chosen as a city to analyze the CCHP system in the cooling season.

Minneapolis has 333 cooling degree days during the cooling season. Table 10 lists the CCHP results during the cooling season in Minneapolis.

**Table 10: Results of Minneapolis Cooling Season**

<i>Energy Type</i>	<i>Value (kWh)</i>	<i>Percentage of Fuel Input</i>	<i>Fraction based upon CDD.</i>
Fuel Consumption	8468.1	-	25.4
Electricity Production	1437.3	17.0%	4.3
Chilled Water Production	870.6	-	2.6
Domestic Hot Water Production	792.8	9.4%	2.4
Tank E <sub>store</sub>	9.4	0.1%	0.0
Desorber Heat Input	2062.4	24.4%	6.2
Heat Captured from PM	4969.6	-	14.9
Pipe Losses	1130.4	13.3%	3.4
PM Losses	2061.2	24.3%	6.2
Tank Losses	974.6	11.5%	2.9

### 6.1.4 Albuquerque, NM

Albuquerque, NM was chosen since it has a hot climate during the summer and is not moderated by any large bodies of water. In addition, its average daily high temperature during the middle of the summer is hotter than the other three cities (Table 13). Albuquerque has 413 cooling degree days during the cooling season.

This is one of the lowest amongst the four cities, but the cooling season is the shortest here as well. This is due to the lower temperatures at night time that compensate for the higher daytime temperatures until the middle of the summer. Results for Albuquerque are detailed in Table 11.

**Table 11: Results of Albuquerque Cooling Season**

<i>Energy Type</i>	<i>Value (kWh)</i>	<i>Percentage of Fuel Input</i>	<i>Fraction based upon CDD.</i>
Fuel Consumption	6482.6	-	15.7
Electricity Production	1077.3	16.6%	2.6
Chilled Water Production	802.8	-	1.9
Domestic Hot Water Production	357.6	5.5%	0.9
Tank E <sub>store</sub>	5.3	0.1%	0.0
Desorber Heat Input	1955.7	30.2%	4.7
Heat Captured from PM	3820.9	-	9.3
Pipe Losses	882.8	13.6%	2.1
PM Losses	1584.4	24.4%	3.8
Tank Losses	619.5	9.6%	1.5

6.2 Discussion of Results

Much useful information can be gathered from analyzing the data above. In Table 12, a comparison is made between the percentages of energy outputs to fuel input from various cities.

**Table 12: Comparison of Cities as a Percentage of Fuel Input**

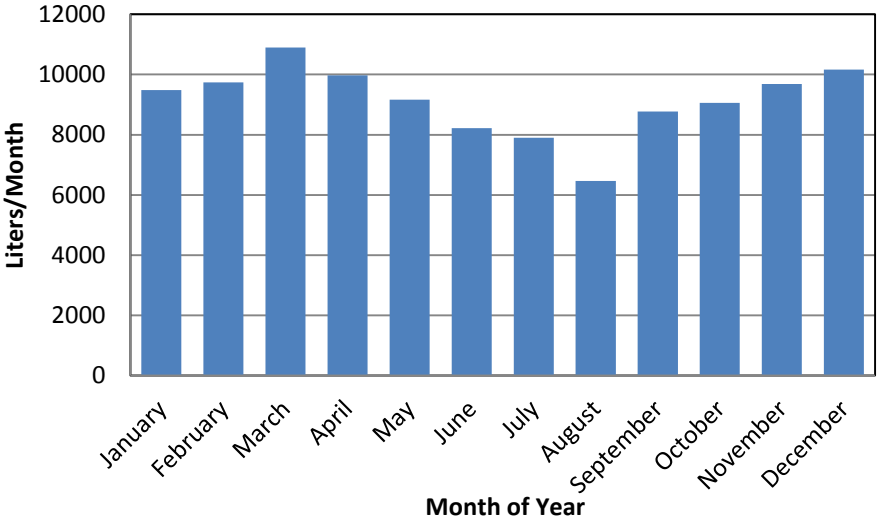
<i>Energy Type</i>	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
Electricity Production	16.9%	16.9%	17.0%	16.6%
Domestic Hot Water Production	8.3%	6.2%	9.4%	5.5%
Tank E <sub>store</sub>	0.1%	0.0%	0.1%	0.1%
Desorber Heat Input	25.0%	27.8%	24.4%	30.2%
Pipe Losses	13.5%	13.5%	13.3%	13.6%
PM Losses	24.4%	24.4%	24.3%	24.4%
Tank Losses	11.8%	11.2%	11.5%	9.6%
<b>Total</b>	<b>100.0%</b>	<b>100.0%</b>	<b>100.0%</b>	<b>100.0%</b>

### 6.2.1 Prime Mover

From this table, it is shown that the prime mover is not affected by changes in weather data. The prime mover converts about 17% of the fuel input into electricity and loses about 24.4% of the fuel input to the environment. This gives an overall efficiency of the prime mover of 75.6%.

### 6.2.2 Domestic Hot Water

These results do not show close agreement between values of the percentage of hot water produced based upon the fuel input. The answer to this is closely tied to the domestic hot water profile that was used to generate the demand on the simulation.



**Figure 34: Annex 42 Load Profile Monthly Consumption**

As Figure 34 shows, there is less consumption specified in the load profile as summer progresses, with the minimum occurring in August. The cities with the cooling season beginning before May and ending after August should have a higher

percentage fuel consumption based upon amount of DHW that is required to be produced. Albuquerque, with the shortest cooling season that only covers the lowest profile months, has the lowest percentage of DHW to fuel input of the four cities.

However, if the amount of energy required to supply the DHW over the cooling season is considered, the city with another relatively short cooling season, Minneapolis, has the greatest energy required. The reason for this is the relative percentage of DHW required when compared to the load of the adsorption chiller, as shown in the next section.

### 6.2.3 Adsorption Chiller

Miami and Albuquerque have the highest percentage of energy utilized to provide cooling. This is as expected since the average daily high temperature in these locations is much higher than the other two cities. Since Albuquerque’s daily high temperature is even higher than Miami’s temperature, it requires an even greater percentage of the fuel input. This is shown in Table 13.

**Table 13: Adsorption Chiller Location Comparison**

	<i>Percentage of Fuel Input Required for Cooling</i>	<i>Average Daily High Temperature (°C)</i>
College Park, MD	25.0%	28.6
Miami, FL	27.8%	28.8
Minneapolis, MN	24.4%	26.2
Albuquerque, NM	30.2%	32.5

### 6.3 Extension of Applicability

An attempt was made to allow comparison of the cooling degree days of a city with the performance of this CCHP system. The process implemented was that if a city’s

CDD were known, then the consumer would know the performance of the system and as an extension, the costs that apply in any city. However, as shown in Table 14, there does not appear to be a direct correlation between the CDD of a city and the performance of this CCHP system.

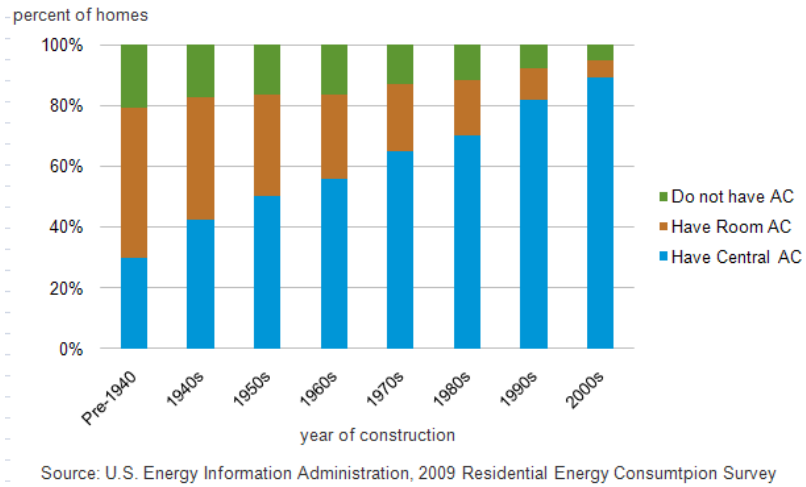
**Table 14: Comparison of Cites per Fraction of CDD**

<i>Fraction of CDD</i>	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
Fuel Consumption	17.6	12.1	25.4	15.7
Electricity Production	3.0	2.0	4.3	2.6
Chilled Water Production	1.9	1.4	2.6	1.9
Domestic Hot Water Production	1.5	0.7	2.4	0.9
Tank $E_{store}$	0.0	0.0	0.0	0.0
Desorber Heat Input	4.4	3.4	6.2	4.7
Heat Captured from PM	10.3	7.1	14.9	9.3
Pipe Losses	2.4	1.6	3.4	2.1
PM Losses	4.3	2.9	6.2	3.8
Tank Losses	2.1	1.4	2.9	1.5

#### 6.4 Primary Energy Ratio

According to the US EIA, more and more homes are outfitted with air conditioning units, with an increased focus towards installing central air conditioners. This is detailed in Figure 35. In order for a direct comparison to be made between a traditional home with a central air conditioner and the CCHP system discussed above,

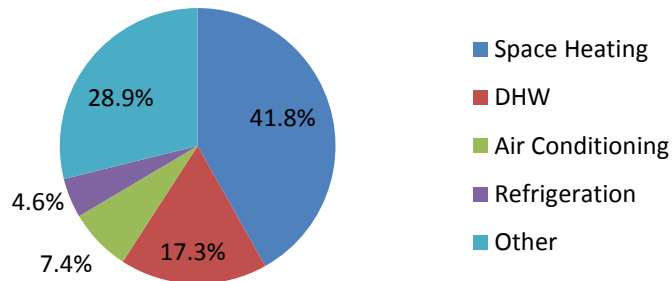
a common unit of measurement will need to be utilized. The Primary Energy Ratio (PER) will be employed for comparison of the two systems over the cooling season.



**Figure 35: Air Conditioning in US Homes**

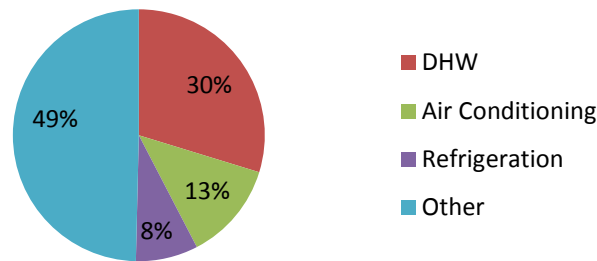
#### 6.4.1 Average Household Energy Use

Prior to being able to compare the PER for the two systems, an understanding of the average energy use of a US household will be required. In 2009, the average US household consumed 26,279.4 kWh of electricity, which is broken down into component parts detailed in Figure 36.



**Figure 36: Average Household Energy Use in US, 2009**

Since only the cooling season is of interest, the electricity used for space heating is not included for this analysis, as shown in Figure 37. The ‘Other’ category includes electricity used for household items such as cooking appliances, clothes washer and dryers, dishwashers, electronics, and lighting (U.S. Energy Information Administration, 2012).



**Figure 37: Cooling Season Average Household Energy Use in US, 2009**

For calculation of the PER of the CCHP system, the average electrical use of a home in the US is required. It is needed to determine if the electrical output of the CCHP system is enough to meet the demand of a nominal US household. It will be calculated by adding the energy required by the refrigerator and the ‘other’ energy loads of the house, which totals 9,085.2 kWh per year. This value will then be reduced to the applicable city’s cooling season.

#### 6.4.2 Traditional Building

Using the data provided by the EIA (Figure 37) gives the total energy consumed by an average US household. Since this encompasses all loads on the building and the required energy used to cover these loads, the PER of an average household in the US in 2009 is 0.350, which is the average electrical grid efficiency.



### 6.4.3 CCHP System

To determine the PER of the CCHP system, a summary of the outputs is required first, which are listed in Table 15. As shown, the electricity produced by the prime mover does not fully meet the demand of the household based upon the average US household during the cooling season. The remainder of the electricity is assumed to be provided by the electrical grid, though it could be provided by an onsite solar panel or wind turbine. The PER for the CCHP system is calculated similar to what has been previously described in Equation 1. However, since the CCHP system is not able to provide the necessary amount of electricity, more has to be supplied by the grid and changes the calculation for the PER. By using Equation 3, the additional primary energy that is required to produce the additional electricity for the household is accounted for.

$$PER = \frac{Q_{clg} + Q_{htg} + Q_{dhw} + P_{elec,CCHP} + P_{elec,grid}}{Q_{fuel} + \left(\frac{P_{elec,grid}}{\eta_{grid}}\right)} \quad \text{Equation 3}$$

**Table 15: PER of CCHP System**

<i>City</i>	<i>Q<sub>clg</sub></i> <i>(kWh)</i>	<i>Q<sub>dhw</sub></i> <i>(kWh)</i>	<i>Electricity</i> <i>Produced</i> <i>(kWh)</i>	<i>Electricity</i> <i>Required</i> <i>(kWh)</i>	<i>PER</i>
College Park, MD	933.5	733.9	1495.2	2514.0	0.355
Miami, FL	3022.5	1564.8	4279.0	6795.2	0.349
Minneapolis, MN	870.6	792.8	1437.3	2290.0	0.362
Albuquerque, MN	802.8	357.6	1077.3	1468.6	0.345

As expected, the two cities having the highest average daily high temperature have the lowest PER. This is due to the low COP of the thermal adsorption chiller that offsets the energy utilized for DHW or other electrical loads.

#### 6.4.4 Comparison

As shown above, the PER for the traditional household based upon the average household energy consumption in the US during the cooling season is 0.350. This is slightly better than the PER for Albuquerque and Miami but worse than the other two cities. This is the case for these two cities since the adsorption chiller must provide more cooling due to their hotter climates than College Park or Minneapolis.

There are many factors that would most likely reduce the PER of the traditional household. First, the value is based upon the national grid efficiency. If natural gas fueled power plants supply the electricity, then the PER would increase to 0.419 since these plants have a higher efficiency. An even higher PER would occur if a significant portion of the supplied electricity came from renewable energy sources. If the electric plants nearby were instead fueled by petroleum, then the PER would approach 0.315.

Another factor that reduces the PER of the traditional household are the transmission and distribution losses of the electrical grid. As detailed in Figure 2, these losses account for 7% of the generated electricity or 2.5% of the entire amount of energy consumed to produce electricity in the US. When these losses are included, the PER of the traditional household drops to 0.329. When all these losses are considered, the CCHP system is a logical choice due to energy considerations.

When commercial CCHP systems are purchased and installed, it is expected they include adequate insulation to prevent unnecessary losses. The experimental setup in the laboratory was not optimized for energy loss whereas a commercial system should include that consideration. An additional PER analysis was conducted where the efficiency of the system was improved to an average of 47.0% from an average of 35.5% by negating the pipe and tank losses from the experimental data. The results are shown in Table 16 below.

**Table 16: PER Result for Added Insulation**

<i>City</i>	<i>PER</i>	<i>Percent Difference</i>
College Park, MD	0.44	23.4%
Miami, FL	0.43	23.7%
Minneapolis, MN	0.45	23.9%
Albuquerque, NM	0.43	24.6%

As noticed, the PER of the CCHP system during the cooling season increases dramatically when insulation is added to reduce the losses. The average increase for the four cities is 23.9%. It is noted that these losses will not be entirely reduced in a commercial system. However, this indicates the marked improvement when the losses to the environment are reduced for CCHP systems.

## Chapter 7: Economic and Environmental Analysis

### 7.1 Assumptions

An important part of consumers deciding whether to purchase CHP systems for their homes is the initial and long term cost of that choice. Numerous factors affect this choice. Most of these must be generalized in order to show the overall value of the data analysis. For this analysis, only the cooling season is studied. This analysis follows the simple payback method used by Kong et al. (2003), Hamzehkolaei et al. (2011), and others due to the complexity of including a further detailed economic analysis.

#### 7.1.1 Traditional System

For comparison, the house without a CCHP system is described. This house would use electricity from the grid to provide the necessary services. A natural gas furnace would be used for heat that is 85% efficient, but is not included in this model. Air conditioning is provided by a split system central air conditioner. This system is based upon a Seasonal Energy Efficiency Ratio (SEER) of 13 BTU/W-h, which is the minimum specified by the United States Department of Energy since January 23, 2006 (DOE Office of Energy Efficiency and Renewable Energy, 2001). This seasonal average leads to a COP of approximately 3.5, which is used for this economic analysis. It is understood that there are many other factors that would influence the difference between SEER and COP, but these are not included in order to assist this simplified analysis.

The hot water is heated by an electric hot water heater. As of August 3, 2011, the minimum energy efficiency of electric hot water heaters for federal purchases is  $0.97 - (0.00132 \times \text{Volume of Tank})$  (Products, 2001). Therefore, a 50 gallon electric hot water heater has a 0.904 performance factor. An efficiency of 90% is utilized for this economic analysis.

#### 7.1.2 Experimental CCHP system

Some important assumptions to discuss are that the operating strategy utilized for the simulation. The strategy utilized for the experiment and subsequent analysis is thermal load following with thermal storage. It is assumed that all unused electricity is sold back to the utility company through net metering and any additional electricity is purchased from the electric company.

#### 7.1.3 Energy Cost

The natural gas market has seen a resurgence recently. That has helped reduce prices, making CHP systems potentially more affordable. The peak of natural gas prices was in 2008 at a yearly average of \$13.89 per 1000 cubic feet. The average annual price in 2012 was \$10.68 per 1000 cubic feet. The average for the first three months of 2013 was \$9.26 per 1000 cubic feet. For this economic analysis, a price of \$10.68 per 1000 cubic feet is utilized since it is the last full year of data available. This is equal to \$0.036 per kWh.

The residential consumer price of electricity is dependent on many factors. Many utilities have varying rates based upon season of the year and time of the day that the electricity is utilized, which is referred to as Time of Use (TOU) pricing. Also, the price is region specific. Therefore, for ease of analysis, the average cost of electricity in the United States is utilized for the economic analysis. The U.S. Energy Information Administration (2013) compiles this data and gives a US average price for residential electricity of 11.88 cents per kWh for 2012, the latest yearly data is available. This electricity is provided to over 126 million customers, which makes for a potentially large CHP market.

The net metering buyback price varies greatly across the United States. Forty three states have a policy governing net metering in their state (North Carolina Solar Center, 2013). The prevailing policy is to allow credits of electricity to roll over for up to a year at the current retail rate of that electricity. Then at the end of the year, consumers have an opportunity to be paid for any excess generation, usually at the utility's avoided cost for that electricity generated, not the retail price. Also, the credits for generated electricity usually cannot be applied to the transmission and distribution charges on their electric bill. However, the policies vary from state to state and also if the electricity is generated from renewable resources such as solar or fossil fuels such as natural gas, as in this experiment. To support this economic analysis, it is assumed that the utility buy back price of generated electricity is the same as the average national retail rate of 11.88 cents per kWh.

This assumption also makes the calculations easier and negates the time of use (TOU) variations. Most utilities charge a different usage rate, which usually revolves around the season or time of day that the usage occurs. As an example, during the Summer season in Maryland, one utility charges 13.509 cents per kWh during peak periods during the day (10am-8pm) and 7.337 cents per kWh during off peak times (11pm - 7am). This also affects the net metering buy back rate. By assuming that all electricity used and generated throughout the cooling season has the same price, these factors are negated.

### 7.2 Capital Cost

The capital costs include the cost of the Marathon Ecopower engine, thermal storage tank, and adsorption chiller, along with the associated installation costs. Since most buildings already have existing HVAC ducts and domestic hot water piping systems, those costs will not be included as they are included in the cost of any new or remodeled system. The cost of the prime mover incorporates the parts necessary to connect the CHP system to the grid for net metering purposes. In addition, the cost of the thermal storage tank is included in the cost of the Ecopower engine as they are sold as a package. An Ecopower engine costs between \$35,000 to \$45,000 to have installed, depending on labor costs, differences in building and electrical codes, and facility size (Adams, 2013). Therefore, a capital cost of \$40,000 is assumed for the installation.

Since the adsorption chiller was designed and built in the laboratory, reliable cost data cannot be ascertained on the specific adsorption chiller cost. Other commercial

adsorption chiller prices were found and scaled to a price per kW chiller output. An average was taken and used for the capital cost of the experimental adsorption chiller.

Wang (2009) estimated that the expected adsorption chiller price could reach 1k€/kW when the market is developed from the current initial cost of 2 to 3 times that amount. This is \$2,600/kW to \$4,000/kW for today exchange rate of Euros to US dollar for the new market.

There are currently two companies that market adsorption chillers for the residential market. They are SorTech AG and InvenSor. SorTech AG sells the ACS 08, which has a 7.5 kW cooling capacity and InvenSor sells the InvenSor LTC 10 Plus which has a 10 kW cooling capacity. The SorTech ACS08 costs 10,650€ (\$14,000) (SorTech AG, 2013). This is approximately \$1,850 per kW. The capital cost of the InvenSor LTC 10 Plus is 27,000€ (\$35,800), which is \$3,580 per kW (Schieler, 2013). The reason for the increased cost of the InvenSor LTC 10 Plus is that it is also capable of operating as a heat pump to supply heating when needed.

For this economic analysis, a capital cost of \$2,000 per kW cooling capacity is used. This is based upon using Wang's lower estimate of emerging technologies that have not saturated the market, the SorTech AG ACS08 price of \$1,850 per kW, and half of the InvenSor LTC 10 plus cost at \$1,790 per kW. This leads to a capital cost of the adsorption chiller in the experiment of \$6,000.



**Table 17: Capital Cost**

<i>Item</i>	<i>Cost</i>
Marathon Ecopower Engine	\$40,000
Adsorption Chiller	\$6,000
Miscellaneous/Installation	\$4,000
<b>Total</b>	<b>\$50,000</b>

7.3 Payback Time Period

In using the simple payback model, the important result is the pay-back period for the consumer. This is the point at which the higher initial capital costs for the CHP system will save money from the reduced annual expenses when compared to the traditional system. A few equations must be defined in order to aid in this analysis. The first is the payback period. This is defined as when the CHP system has paid for itself and is saving the consumer money.

$$n = CC/AS \quad \text{Equation 4}$$

In Equation 4, the Capital Cost (CC) is based upon the summary in Table 17. The payback period (n) is the desired outcome of the equation. The annual savings (AS) that the CCHP system generates based on the cooling season is calculated from Equation 5 below.

$$AS = AC - NGI - MC \quad \text{Equation 5}$$

The annual savings (AS) is based upon the operating costs during the cooling season. The natural gas consumption income (NGI) is the cost of the natural gas used by the CHP system to provide the required cooling and domestic hot water. The maintenance cost (MC) is based upon a factor of the electricity generated. As shown in Roselli and Kong, the maintenance cost ranges from 0.025 to 0.03 per kWh of generated electricity. Therefore, 0.03 per kWh is utilized for this assumption (Roselli

and Sasso, 2011) (Kong, Wang, and Huang, 2003). The avoided cost (AC) is based upon the energy that would have been utilized by the traditional system, with representative systems and assumptions detailed above. The below equation details the avoided cost for the cooling season. Since only the cooling season is covered, the energy that would have been utilized by the furnace for heating is neglected.

$$AC = CI + EI + DHWI \quad \text{Equation 6}$$

The avoided cost is based upon the price of electricity purchased to provide the cooling and ancillary electrical needs of the house. Table 18 below details the equations used for the simple payback period analysis.

**Table 18: Parameters for Payback Period Analysis**

<i>Parameter</i>	<i>Equation</i>
Annual Power Generation Cost	$EI = EP * \Sigma P_{elec}$
Annual Cooling Cost	$CI = EP * \frac{\Sigma Q_C}{COP}$
Annual DHW Cost	$DHWI = EP * \Sigma Q_{DHW}$
Natural Gas Cost	$NGI = NGP * NGU$
Maintenance Cost	$MC = 0.03 * \Sigma P_{elec}$
Capital Cost	$CC = \$50,000$
Natural Gas Price	$NGP = \frac{\$10.68}{1000 \text{ ft}^3}$
Electricity Price	$EP = \$0.1188/kWh$
COP	$COP = 3.5$

**Table 19: Payback Period Analysis**

	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
EI	\$177.63	\$508.35	\$170.75	\$127.98
CI	\$31.69	\$102.59	\$29.55	\$27.25
DHWI	\$87.19	\$185.90	\$94.18	\$42.48
NGI	\$314.82	\$903.10	\$301.95	\$231.15
MC	\$44.86	\$128.37	\$43.12	\$32.32
AC	\$296.50	\$796.84	\$294.49	\$197.72
AS	-\$63.18	-\$234.63	-\$50.58	-\$65.75
n	N/A	N/A	N/A	N/A

As can be seen from the analysis, the CCHP system for four cities costs more to run each cooling season than what the cost would be to provide the same outputs for the traditional electric grid. This is expected due to the low COP of the adsorption chiller compared to the high COP of the VCS air conditioners.

When commercial CCHP systems are purchased and installed, it is expected they include adequate insulation to prevent unnecessary losses. The experimental setup in the laboratory was not optimized for energy loss whereas a commercial system should include that consideration. An additional economic analysis was conducted where the efficiency of the system was improved to an average of 47.0% from an average of 35.5% by negating the pipe and tank losses from the experimental data. The results are shown in Table 20 below.

**Table 20: Payback Period Analysis with Added Insulation**

	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
NGI	\$235.37	\$680.35	\$226.89	\$177.58
AC	\$296.50	\$796.84	\$294.49	\$197.72
AS	\$16.28	-\$11.88	\$24.48	-\$12.19
Additional Savings/year	\$79.45	\$222.75	\$75.06	\$53.57
Payback Period (years)	3,070	N/A	2,040	N/A

As indicated above, the CCHP system costs more to run each year in two of the cities that buying electricity from the grid during the cooling season. In Maryland and Minnesota, the CCHP system would save money, but the payback period would be

greater than the lifetime of the system itself. However, this analysis shows the added benefit of using insulation.

Since electricity and natural gas prices vary between the locations simulated, another economic analysis was conducted to investigate the significance of this difference.

The state-by-state price data from 2011 was obtained from the EIA and included in Table 21.

**Table 21: Electricity and Natural Gas Cost by State**

<i>State</i>	<i>Electricity (\$/kWh)</i>	<i>Natural Gas (\$/1,000 ft<sup>3</sup>)</i>
Maryland	0.1331	12.10
Florida	0.1151	18.16
Minnesota	0.1096	8.85
New Mexico	0.1100	9.14
US Average	0.1188	10.68

This study will include the benefits of the added insulation where pipe and tank losses are neglected. The conclusion is detailed in Table 22.

**Table 22: Payback Period Analysis with Local Utility Rates**

	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
NGI	\$266.66	\$1,156.85	\$188.01	\$151.98
AC	\$332.19	\$772.02	\$271.68	\$183.07
AS	\$20.67	-\$513.20	\$40.55	-\$1.23
Payback Period (years)	2,420	N/A	1,230	N/A

By adding in the state average price for utilities, the cooling season out-of-pocket expense changes dramatically. The two cities with the highest state average cost of utilities make the decision to purchase a CCHP system more difficult based upon the cooling season. Some states do offer incentives that could reduce parts of these additional costs.

7.4 Emission Reduction

Another potential benefit of micro CHP plants is the reduction of emissions into the atmosphere. According to the US EIA, the United States produced 2,766.8 billion kWh of electricity from fossil fuel power electricity generating plants in 2010 (U.S. Energy Information Administration, 2013). This led to the release of 2,388,596 thousand metric tons of CO<sub>2</sub>, 5,400 thousand metric tons of SO<sub>2</sub>, and 2,491 thousand metric tons of NO<sub>x</sub>. These emission results for the electric grid will then be compared to the emission results from the Marathon Ecopower engine. The results were obtained from product brochures detailing the benefits of the CHP engine (Marathon Engine Systems, 2012), which is summarized in Table 23 below.

**Table 23: Comparison of Emissions**

<i>Emission Gas</i>	<i>Traditional Grid (kg/MWh)</i>	<i>Ecopower (kg/MWh)</i>	<i>Percent Reduction</i>
CO <sub>2</sub>	863.3	327	-62.1%
SO <sub>2</sub>	1.95	Trace	-100%
NO <sub>x</sub>	0.90	0.03	-96.7%

As shown, there is significant reduction in emissions for all three gasses. By extrapolation, when there is more CHP proliferation into the residential energy market, the reduction of emissions will be even greater. Any CCHP system installation using the Marathon Ecopower prime mover will reduce the overall emissions output. A more region and site specific calculation of emission gas reduction by CHP plants is given by the CHP Partnership of the EPA (2012). As an example of this, the PJM electrical region of the US, which serves the Mid-Atlantic region, lists the air emissions reiterated in Table 24. By using region specific numbers, more accurate emissions reduction data for the CHP system will be

obtained. Region emission data varies based upon the type of electricity generating plants that supply electricity to that portion of the grid, whether renewable, nuclear, or fossil fuel based plants.

**Table 24: PJM Grid Emission Data**

<i>Emission Gas</i>	<i>kg/MWh</i>
CO <sub>2</sub>	495.3
SO <sub>2</sub>	1.09
NO <sub>x</sub>	0.43

If the United States were to increase its share of CHP production from 8% to 20% by 2030, Oak Ridge National Laboratory estimates that the increased efficiency would save 5.3 Quads (quadrillion BTUs) annually, which is about half the energy consumed by the residential sector. CO<sub>2</sub> emissions would be reduced by 848 million metric tons, which would be 60% of the CO<sub>2</sub> released between now and 2030.

Other researchers have also analyzed the reduced emissions when utilizing CHP technology. Fatemeh et al. (2011) conducted a study of a CHP system in five different climate locations in Iran with an economic and environmental analysis. He then compared their results with other simulations. Dorer and Weber (2009) performed an analysis of energy and emission data of micro-CHP in Switzerland with a sensitivity analysis of various components.

## Chapter 8: Conclusions

The basic idea of implementing CCHP systems is to reduce the amount of primary energy used, the emission gasses into the atmosphere, and the long term cost.

Through this work, these three factors have been investigated for an experimental CCHP system during the cooling season.

### 8.1 Locations

The four cities chosen to evaluate the feasibility of the CCHP system fulfill various requirements. Geographical separation was needed to assist in meeting the requirements. The cities need to have varied weather climates, but still include a long enough cooling season in the summer to warrant a CCHP system installation.

The highest daily temperature during the cooling season could not exceed 35°C since the adsorption chiller was designed to operate at less than 37°C. This offset is due to a 2 K approach temperature designed between the ambient temperature and condenser temperature. If the adsorption chiller was operational above this range, then erroneous values were generated that invalidated the results. For cities such as Phoenix, AZ where this occurs, a backup VCS air conditioner could be employed or a different adsorption chiller utilized that was designed to operate at these high ambient temperatures.

The cities needed to be in different states that have varied electrical and natural gas prices. This aided in the economic comparison conducted in Table 22. While usually it is convenient to use average prices, a more realistic approach would be to include region specific values when relevant and available.

### 8.2 PER Reduction

A common unit of comparison is needed to evaluate the potential benefits of two different systems. In this case, the PER is best served for this task. It relates the useful outputs to the required primary fuel inputs. Since the CCHP system and traditional electrical grid employ different methods, each PER calculation has its own technique.

For the traditional grid, the average household use of energy is known for the year. Since only the cooling season is being investigated, the heating allotment is neglected. The rest of the energy use is supplied by electricity generated from central power plants provided through the electrical grid. Since the load is known in energy terms, then the PER can be found by the efficiency of the electrical grid, which is 35.0%. Thus, the PER is 0.35, which does not include transmission and distribution losses. If those are included, the PER drops to 0.329 for an average US household. However, this value can reduce to as low as 0.31 if the central power plant is fueled by petroleum or approach infinity if only renewable energy sources are used to provide the necessary loads.



For the experimental CCHP system, the PER was calculated for the four selected cities for the duration of the cooling season. Since the electrical load on the modeled building was not known, the average load on a US household was used instead. This value was higher than the amount produced by the CCHP prime mover, thus the rest was purchased from the grid. The PER of the four cities are repeated below in Table 25. As the PER of CCHP systems increase, less fuel will be required.

**Table 25: PER of Selected Cities**

	<i>Average US household</i>	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
PER	0.350	0.355	0.349	0.362	0.345

These results indicate that from an energy perspective, the CCHP systems are advantageous over the traditional grid for the two cities that require the least cooling. They are even more advantageous for all four cities when transmission and distribution losses are taken into account.

As stated above, the PER of the CCHP systems increase dramatically when renewable energy supplies are used to produce the necessary output. Solar panels could be attached to the roof of the building and generate electricity to meet part of the site demand or generate hot water that could be used to heat the thermal storage tank. If both types of panels are installed on site and with sufficient quantity, the prime mover becomes a backup source of thermal energy and electricity when needed. The CCHP system could also be integrated with wind or hydroelectric power, though these are uncommon.

### 8.3 Emission Reduction

As was covered in Chapter 7, emission reduction is one goal of CCHP systems. The company that designed and built the Ecopower engine allotted effort in reducing the emission output. When its output is compared to the electric grid as a whole in the US, each Ecopower prime mover installed in CHP systems reduces the amount of emission gas released to the atmosphere. Most of this is based upon the type of fuel that the Ecopower engine utilizes. The electrical grid employs natural gas, petroleum, wood, and coal fueled power plants that make up the total emission output. Another factor is the reduced energy consumption. As the PER of CCHP systems increase, less fuel will be required and thus less emissions will be produced.

### 8.4 Simple Economic Analysis

While the experimental CCHP system shows benefits concerning energy and emissions, the trend does not continue into economics. The major reason for this is that the COP of the adsorption chiller is much lower than that of the VCS air conditioner. However, much insight is gained when evaluating the out-of-pocket expense during the cooling season for CCHP systems.

All four cities had a negative cooling season cash flow. The amount changes drastically when the added insulation effects are considered and when state specific utility prices are considered.

When insulation is added to the CCHP system, the negative cooling season cash flow reduces by over 80% for each location. This emphasizes the importance of the

insulation and proves to potential customers its benefit. Even though two of the cities show a positive annual cash flow with added insulation, the long time period still makes the implementation not feasible based upon economic concerns.

When actual state average utility costs are employed in the economic analysis for the CCHP system with added insulation, the ending result is much different than when using average national prices for electricity and natural gas.

**Table 26: Economic Comparison for Utility Prices**

<i>Annual Saving</i>	<i>College Park, MD</i>	<i>Miami, FL</i>	<i>Minneapolis, MN</i>	<i>Albuquerque, NM</i>
AS - US avg.	\$16.28	-\$11.88	\$24.48	-\$12.19
AS - State avg.	\$20.67	-\$513.20	\$40.55	-\$1.23

As detailed in Table 26, the states with the highest utility costs show a marked jump in out-of-pocket expenses during the cooling season.

8.5 Summary

When all three factors above are considered for the cooling season, the best city of the four analyzed to implement the experimental CCHP system is in Minneapolis, MN. It has the highest annual savings for the cooling season and the highest PER. This was unexpected since it is located the farthest North of the four cities, has a relatively short cooling season, and has the lowest daily high average temperature. The major cause of this is that Minnesota has the lowest utility rates when compared to the other four states, and its average cost of natural gas is half of Florida’s cost.

## Chapter 9: Future Recommendations

This thesis has shown the validity of a CCHP system during the cooling season in four locations across the United States. The simulation model was validated against a test of an experimental CCHP system conducted in the laboratory. After reviewing the results, there are many ideas that could potentially offer improvement with this CCHP system.

### 9.1 Prime Mover

The prime mover utilized was a SI-ICE. However, as noted in Chapter 2, there are many different types of prime movers that could be utilized. A promising one is a proton exchange membrane fuel cell (PEMFC). TRNSYS includes these types of fuel cells that could be compared against actual performance data to extrapolate results for the year. Fuel cells have potentially the most promise since they are more adequately suitable for scaling to residential requirements.

Other types of prime movers could be used, but each has their own drawbacks and are not yet suitable for micro CCHP applications. Continued research into Stirling engines and gas turbines could produce viable alternatives however.

### 9.2 Annual Simulation

This thesis only covered the cooling season since the experiment that the simulation was conducted after only used cooling. This would be readily implemented into the TRNSYS simulation model as a load imposed onto the thermal storage tank. The

difficult portion would be to correctly model the supply and return tank temperatures of the water. This could effectively be employed with another secondary heat exchanger that contained the circulated hot water loop. This would be tricky to implement in the shoulder season, as the control strategy for the thermal storage tank would change often. During the cooling season, it is required to remain stratified for operation of the adsorption chiller whereas in the heating season it is more advantageous to have the entire tank at the hot temperature to reduce the number of times the prime mover cycles.

By including the heating season analysis, the true potential cost benefit of CCHP systems could be studied for various locations. As detailed above, the CCHP system does not make economic sense if only operated during the cooling season. The heat load on the house during the heating season will make the economic analysis potentially in favor of the customer. Since the heating in most homes across the US is supplied by a boiler with 85% efficiency, much more energy is required to meet the heating load than with a VCS air conditioner to meet the cooling load due to the high COP.

### 9.3 Renewable Energy

Another interesting addition, as noted previously, would be the addition of renewable energy sources to the CCHP system. The most realistic addition would be solar panels, whether they are used to produce electricity or hot water. Ideally they would do both. Other options are available, but do not currently possess the ability to saturate the consumer market.

If solar panels are included with the CCHP system, then both types should be installed. The solar thermal collectors could send the hot water to the thermal storage tank. The PV solar panels could offset the electricity load of the household and potentially generate income for the owners if enough capacity is installed to fully offset the household electrical load. If both types are used, then the prime mover would then become the backup source of thermal source and tertiary source of electricity, if connected to the grid.

This detailed system with solar panels could then be implemented into TRNSYS. Data is readily available for the performance of solar panels and TRNSYS has a robust collection of models to aid in the simulation. The most difficult portion would be designing and implementing a control strategy. This option will have the best opportunity to save the customers money annually, but may have a long payback period due to high initial costs.

## Nomenclature

AC – Avoided Cost

AS – Annual Saving

BTU – British Thermal Unit

CC – Capital Cost

CCHP – Combined Cooling, Heating, and Power

CDD – Cooling Degree - Days

CHP – Combined Heating and Power

CI – Cooling Income

CO<sub>2</sub> – Carbon Dioxide

COP – Coefficient of Performance

DHW – Domestic Hot Water

DHWI – Domestic Hot Water Income

DOE – Department of Energy

EI – Electricity Income

EIA – Energy Information Agency

EPA – Environmental Protection Agency

E<sub>pm</sub> – Instantaneous Electric Load Generated by PM

E<sub>store</sub> – Instantaneous Change in Energy Stored in Thermal Storage Tank

$\eta_{\text{grid}}$  – Electrical Efficiency of the Grid

HVAC – Heating, Ventilation, and Cooling

IEA – International Energy Agency

MC – Maintenance Cost

n – Payback Period

NGI – Natural Gas Income

NO<sub>x</sub> – Nitrogen Oxides

P<sub>elec,CCHP</sub> – Electricity Generated by CCHP system

P<sub>elec,grid</sub> – Electricity Required to be Supplied by the Grid

PEMFC – Proton Exchange Membrane Fuel Cell

PER – Primary Energy Ratio

PLR – Part Load Ratio

PM – Prime Mover

PV – Photo Voltaic Panel

Q<sub>chw</sub> – Chilled Water Load

Q<sub>clg</sub> – Chilled Water Load

Q<sub>dhw</sub> – Domestic Hot Water Load

Q<sub>fuel</sub> – Fuel Load on the PM

Q<sub>htg</sub> – Heating Load

SI-ICE – Spark Ignition Internal Combustion Engine

SO<sub>2</sub> – Sulfur Dioxide

SSLC – Separate Sensible and Latent Cooling

T<sub>chw</sub> – Temperature of Chilled Water Leaving Adsorption Chiller

TMY – Typical Meteorological Year

TOU – Time of Use

TRNSYS – TRAnNsient SYstem Simulation Program

VCS – Vapor Compression System



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