Energy and Exergy Analyses of District Heating and Cooling Systems for Improvements in Sustainability and Performance

A Thesis

Presented in Partial Fulfilment of the Requirements for the

Degree of Master of Science

with a

Major in Mechanical Engineering

in the

College of Graduate Studies

University of Idaho

by

Marc Alexander Compton

Major Professor: Behnaz Rezaie, Ph.D.

Committee Members: Steven Beyerlein, Ph.D.; Dan Cordon, Ph.D.

Department Administrator: Steven Beyerlein, Ph.D.

May 2018

Authorization to Submit Thesis

This thesis of Marc A. Compton, submitted for the degree of Master of Science with a Major in Mechanical Engineering and titled "Energy and Exergy Analyses of District Heating and Cooling Systems for Improvements in Sustainability and Performance," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ________________________________ Date: ______________
Behnaz Rezaie, Ph.D.

Committee Members: ________________________________ Date: ______________
Steven Beyerlein, Ph.D.

________________________________ Date: ______________
Dan Cordon, Ph.D.

Department Administrator: ________________________________ Date: ______________
Steven Beyerlein, Ph.D.

Abstract

To advance long-term sustainability at the University of Idaho (UI) energy plant, energy and exergy losses are quantified and equipment improvements are prioritized accordingly. Emissions from biomass and natural gas are compared to show the impact of moisture content in the biomass versus the heating value of the biomass. The pressure reducing valve (PRV) restricts potential improvements from adjusting steam pressure, however replacing the PRV with a steam turbine results in increased system energy and exergy efficiencies while providing economic benefits by generating electricity. Utilizing waste to energy technology at UI energy plant provides opportunity to use municipal solid waste (MSW) as fuel and reduces the regional environmental impacts from waste on soil, water, and air while saving the landfills.

Acknowledgements

I would like to thank the College of Engineering at the University of Idaho, the Walter C. Hayes Engineering Scholarship, and the Richard B. Stewart Thermodynamics Scholarship for their financial assistance these past years. I would also like to thank Dr. Behnaz Rezaie for her knowledge, supervision, encouragement, and financial support and finally Scott Smith for his patience and technical expertise; without their help this work would not have been possible.

Dedication

To my grandfather, who taught me that anything worth doing, is worth doing right.

Table of Contents

List of Figures

List of Tables

List of Nomenclature

A	Ash yield
AF	Air fuel ratio
BDMT	Bone dry metric ton
BDT	Bone dry ton
boost	Booster
C	Cost ($)
CHCP	Combined heating, cooling, and power
CHP	Combined heating and power
Cond	Condensate
CT	Condensate tank
DA	De-aerator
DE	District energy
E	Energy
econ	Economizer
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FC	Fixed carbon
FD	Forced draft
feed	Feed water
fr	Fraction
g	Gravitational constant
GHG	Greenhouse gas

h	Specific enthalpy (kJ/kg)
HDPE	High-density polyethylene
HHV	Higher heating value (MJ/kg)
HLS	Hot lime softener
HV	Heating value (kJ/kg)
ID	Induced draft
LDPE	Low-density polyethylene
LHV	Lower heating value (MJ/kg)
LLDPE	Linear low-density polyethylene
M	Moisture
M_{air}	mass of air (kg/kmol)
$\dot{m}$	Mass flow rate (kg/s)
M_{fuel}	mass of fuel (kg/kmol)
MSW	Municipal solid waste
n	Number of moles
NG	Natural Gas
P	Pressure (kPa)
PET	Polyethylene terephthalate
PH	Air preheater
PP	Polypropylene
PRV	Pressure reducing valve
PS	Polystyrene
PTA	Percent theoretical air
PVC	Polyvinyl chloride

$\dot{Q}$	Heat transfer rate (kW)
RT	Refrigeration ton
s	Specific entropy (kJ/kg-K)
T	Temperature (°C or K)
TES	Thermal energy storage
UF	Under-fire
V	Velocity (m/s)
VM	Volatile matter
W	Waste
WTE	Waste to energy
$\dot{X}$	Exergy rate (kW)
y	Mole fraction (%)
z	Height (m)

Subscripts

0	Reference property
act	Actual
b	Boundary
des	Destroyed
f	Flow
mol	Molar
p	Combustion products
sys	System
X	Exergy

Chemical symbols

C	Carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen
H_2O	Water vapor
N_2	Nitrogen
O_2	Oxygen
SO_2	Sulfur dioxide

Greek letters

η	Efficiency
ν	Stoichiometric coefficient
ξ	Mole coefficient
ψ	Specific exergy (kJ/kg)

Chapter 1: Introduction

1.1 Motivation

The ever-increasing need for energy is one of mankind's biggest challenges. For a long time, this need has been satisfied by using fossil fuels such as coal, oil, natural gas. Some of the problems associated with energy generation are ocean acidification, air pollution, ozone depletion, and global climate change from greenhouse gases (GHGs). While there is much debate over the use of fossil fuels, GHG concentrations have increased dramatically since the industrial revolution and fossil fuel reserves will eventually be depleted. Since all real world processes impact the environment in some manner, this suggests that some environmental concerns can be addressed through increasing energy efficiency [1]. The need to leave behind an environment suitable for future generations has also led to developments into renewable energy technologies to replace fossil fuels. Solar, wind, geothermal, and biomass are some of the most well-established and promising renewable energy technologies, however renewables are not yet capable of meeting our entire energy requirements. These alternative energy resources, together with increasing energy efficiency, are two common approaches for solving energy related environmental issues like GHG emissions.

District energy (DE) systems can integrate both solutions to meet energy demands: implementing renewable energy technologies and increasing energy efficiency. DE systems provide an opportunity to take advantage of multiple energy resources, whether they are fossil fuels or renewables, to produce heating, cooling, or electricity. By utilizing a central plant and underground piping networks, DE systems eliminate the need for less efficient heating and cooling equipment in individual buildings. This means that in certain conditions, using local energy sources such as solar, biomass, geothermal, and waste heat can be more viable economically and/or environmentally than when using fossil fuels.

An exergy analysis can provide a better understanding of the magnitude and sources of losses in a system compared to an energy analysis [2]. This is because exergy is not conserved in a real process, whereas energy is always conserved. An exergy analysis can provide a means to investigate the environmental impacts from an energy system by advancing the more efficient use of energy resources [3]. The exergy analysis techniques in this thesis can be applied to improve performance in thermal systems. Economics is one of the largest, if not *the* largest, motivators for harnessing energy resources. Operating costs, fuel costs, and equipment costs have great impacts on the total cost. Adjusting operating conditions often has financial and environmental impacts. The goal of this thesis is to suggest technological and operational improvements in the University of Idaho (UI) district energy system to improve the efficient use of energy resources, which in turn results in environmental sustainability advancement as well as financial benefits.

1.2 Objectives

The UI energy plant produces an average of 120 million kg of steam annually which is transported to the core of campus buildings for space heating and cooling, domestic hot water, food preparation, and research purposes. A 2100 kW lithium bromide, single effect absorption chiller uses steam as well to produce chilled water for cooling needs on campus. As of 2018, the district heating and cooling network at UI includes one 18.3 MW biomass fueled boiler, three natural gas boilers with a combined rating of 50.4 MW, two steam driven absorption chillers with a total capacity of 6300 kW, four centrifugal vapor compression chillers with a combined capacity of 8800 kW, and a thermal energy storage (TES) tank with a chilled water capacity of 7500 m^3.

This thesis is focused on calculating the energy and exergy losses in the district heating and cooling plant at the University of Idaho, Moscow campus in Idaho, USA as well as prioritize the highest exergy losses to address environmental impacts, accordingly. The objectives are summarized as the following:

1) To show the potential to improve the energy and exergy efficiency of the UI district energy plant
2) To prioritize equipment modifications for advancing environmental sustainability
3) To investigate feasibility of different scenarios for turbine integration with the steam plant
4) To provide recommendations for the UI energy plant performance improvements

1.3 Outline

This thesis includes six chapters with the intent of improving the sustainability of the UI district heating and cooling system by considering the financial aspects of improvements, via reduced fuel consumption. The UI energy plant, as part of the district heating and cooling system at the Moscow campus, has been operating for over 90 years and many advancements have been made over its lifetime. Chapter 2 focuses on investigating the boiler evolution in the energy plant and their environmental impacts. Each of the four boilers has a different equipment configuration. Energy and exergy efficiencies of each boiler are calculated. Biomass is the main fuel type used in the energy plant while natural gas is used as a backup. Combustion models of both fuels are compared with testing results to determine GHG emissions.

An exergy analysis of the steam cycle and biomass boiler in the energy plant is developed in Chapter 3. Exergy destruction rates through the components of the steam cycle are quantified to identify where improvements to the system would have the most impact in improving performance and sustainability. Parametric studies are conducted and compared with literature to determine the environmental impacts of adjusting boiler steam pressure levels.

A pressure reducing valve (PRV) is used to regulate the steam pressure before use in campus buildings. To reduce pumping costs, boiler steam pressure is kept low. This mode of operation limits potential improvements in the energy plant, both in terms of sustainability and economics. In Chapter 4, replacing the PRV with a small steam turbine and adding a double effect absorption chiller to the cycle is investigated. The exergy analysis from the previous chapter is expanded into a transient model with multiple configurations to determine exergy efficiency and potential fuel savings for the system. TRNSYS software is used for modeling and simulation.

Using biomass at the energy plant allows UI to have a significantly reduced environmental impact while benefiting from substantial economic savings. Natural gas boilers are used as backups when the biomass boiler cannot meet the peak load demands. In Chapter 5, a feasibility study of waste to energy (WTE) technology is conducted. WTE technology has been shown to be one of the means of addressing the impacts that landfills have on the environment. Impacts on soil, water, and air resources in the region can be reduced when municipal solid waste (MSW) is used as fuel for steam generation in the UI energy plant. The composition of MSW generated on campus is calculated to determine its suitability for use in the WTE process. The potential steam load that can be met using MSW derived fuel, economic savings, and net impact on the environment through GHG emissions are also estimated.

Chapter 6 summarizes the findings from all of the previous chapters, as well as operational recommendations for improving the sustainability and performance of the UI energy plant. Furthermore, areas for future study are suggested where the plant would benefit from additional research and potential modifications.

Chapter 2: An Enviro-Exergy Sustainability Analysis of Boiler Evolution in District Energy Systems

M. Compton and B. Rezaie, "An enviro-exergy sustainability analysis of boiler evolution in district energy systems," *Energy*, Vol. 119, pp. 257-265, 2017.

2.1 Abstract

Investigations into energy resources are important from the point of energy sustainability. The principal objective of this study is to investigate the evolution of the operating boilers at the University of Idaho (UI) district energy plant through an exergy analysis. The biomass boiler uses western red cedar chips from nearby lumber mills and provides 95% of the steam requirements of the main campus of UI in Moscow, ID, USA. Thermodynamic analysis reveals a thermal efficiency of 76% and an exergy efficiency of 24% for the biomass boiler. A combustion model is developed to determine the primary emissions products of both the bone dry wood chips and natural gas fuels. CO_2 comprises 26% of the bone dry biomass emissions and 8% of the natural gas emissions products. Testing results of the biomass boiler exhaust stack show CO_2 emissions of 14% when an average moisture content of 33% is accounted for. An overview of the evolution of the energy plant is discussed, showing the generational differences in each boiler. By using a biomass fuel source, the cost per 1000 kg of steam produced is on average 63% lower than using natural gas, resulting in savings of over $1 million annually.

2.2 Introduction

Fossil fuels such as oil, coal, and natural gas are the largest sources of energy in the world today and there is much debate on how much longer production especially can continue to grow, with many suggesting the peak will happen within the next century [4]. In addition to the need for new energy sources to replace fossil fuels, the greenhouse gas (GHG) emissions created after combustion have negative impacts on the environment. While renewable energy generation is growing in an attempt to reduce emissions, development is not at a point where they can replace fossil fuels [5].

These greenhouse gases trap heat when they absorb radiation and contribute to climate change. While the primary greenhouse gases including carbon dioxide (CO_2) occur naturally, concentrations since the pre-industrial era have increased substantially due to human activity [3].

CO_2 is the largest contributor to greenhouse gas emissions due to the combustion of fossil fuels [7]. In the United States alone, over 5.5 billion metric tons of CO_2 was produced in 2014 by fossil fuels [8]. Major CO_2 emissions trends in the US, shown in Figure 2.1, indicate decreases in the use of petroleum and coal while cleaner burning natural gas use has increased. Investing in other sources of energy, such as biomass, can further help reduce the release of CO_2 to the atmosphere. One of the most distinctive characteristics of biomass energy sources is that they are considered to be carbon neutral since the CO_2 released during combustion or other conversion processes will be re-captured by the regrowth of the biomass through photosynthesis [9]. The combustion of fossil fuels on the other hand generates a net increase in CO_2 as the trapped carbon is released into the atmosphere. It is important to note however that while biomass does not contribute to rising global CO_2 levels, it does generate pollutants such as SO_x, NO_x, and HCl [10]. In comparison to other fuels, these pollutants are generally at lower levels than fossil fuels, especially coal.

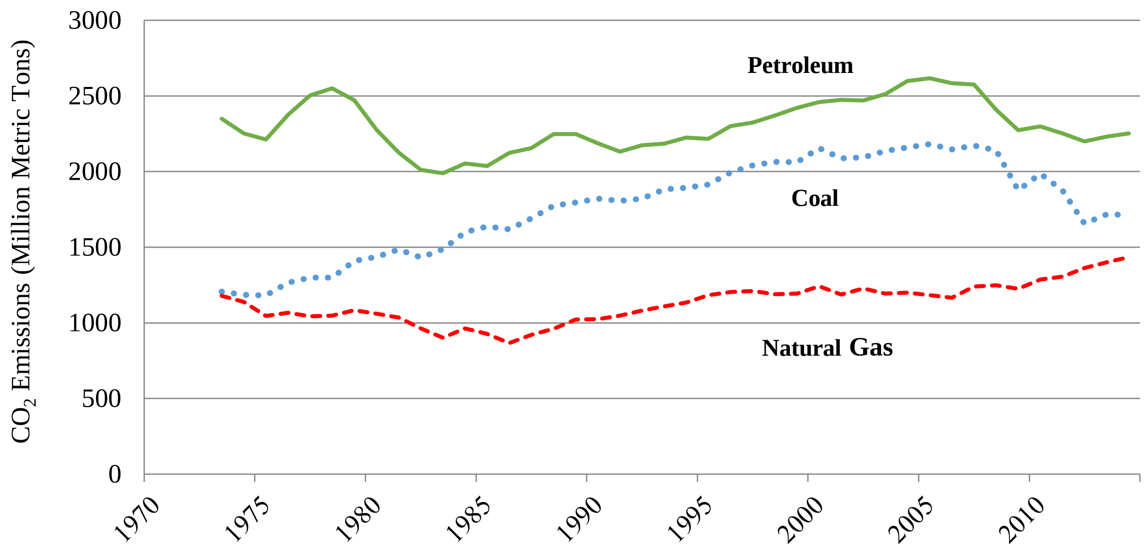

Figure 2.1. U.S. CO_2 emissions from energy consumption by major source from 1973 to 2014 [8].

District energy (DE) has been shown to be an energy efficient means of providing thermal energy with reduced environmental impacts, such as CO_2 production, compared to more conventional systems [11], [12]. Case studies have been reviewed by Lake, et al investigating identification, energy sources, and design considerations of DE systems in the near future [13]. Work has also been done to link CO_2 emissions with the increased economic costs beyond that of reduced efficiency due to carbon taxes associated with the use of fossil fuels [14], [15]. District energy systems produce low pressure steam, hot water, and/or chilled water for use in multiple buildings. Using a centralized production plant and underground piping networks allows for thermal energy to be transported for both heating and cooling needs [16]. This eliminates the need for less efficient heating and cooling equipment for each building. Energy can be sourced from fossil fuels, geothermal, solar, biomass, or industrial waste heat, among others, and DE systems can be more economically feasible based on the proximity of these energy sources.

Biomass is an organic substance derived from plant and animal wastes which can be used as a fuel source. Energy production from biomass involves the use of a wide range of technologies to produce steam, electricity, and fuel [17]. Biomass is generally considered to be a form of renewable energy because there is not a limit to the source. Because biomass is organic, it is one of the most abundant fuels available. Potential sources include wood, animal wastes, industrial residue, agricultural wastes, municipal solid wastes, and a host of other materials [18].

Due to the diverse forms of biomass, there are many ways to utilize it besides direct combustion. Research is being conducted on converting biomass resources into higher-value products such as liquid and gaseous fuels, which could result in potentially more efficient fuels [19]. In addition to this, one method for taking advantage of the clean, abundant nature of biomass is to co-fire it with coal. Co-firing can be implemented with minimal capital investment using current technologies, thus providing a means of reducing GHG emissions in the near future [20]. This is a relatively easy and economical way to generate steam while reducing CO_2, NO_x, and SO_x levels normally produced by combusting coal [21].

Exergy can provide a means to measure potential impacts on the environment from an energy source [3]. Unlike energy, exergy is not a conserved quantity and an exergy balance can account for inputs, losses, and wastes of a process [22]. By analyzing and improving the exergy efficiency of a process, fuel consumption can be reduced while meeting the same energy demands.

Boilers play a critical role in any district energy system and comprise a significant portion of U.S. energy consumption [23]. Because of this, it is important that fuel is consumed in an efficient and sustainable manner to minimize the production of greenhouse gases. In this paper a case study is developed to investigate the sustainability and boiler evolution of the district energy plant through an exergy analysis at the main University of Idaho campus in Moscow, ID, USA. These boilers consist of a primary biomass fed boiler and three previous generations of natural gas fueled boilers. A conventional analysis based on the first law of thermodynamics is conducted, followed by an additional analysis based on the second law of exergy. The mathematical model is developed to analyze the emissions products after combustion of the different fuels. These methods allow for the environmental and economic impacts of using biomass versus natural gas fuels to be evaluated. The mathematical model for the biomass fueled boiler is then compared to measurements taken from the exhaust stack of the boiler.

2.3 Methodology

Engineering Equation Solver (EES) V9.911 was used for all calculations in this study.

2.3.1 Heating Values

The heating value (HV) of a fuel is a measure of the thermal energy that can reasonably be obtained from a fuel [24]. Heating values offer a way to define the efficiency of a system based on the combustion of the fuel used.

In comparison to fossil fuels, biomass fuels have relatively low heating values due to their high moisture and oxygen contents. The general heating value of natural gas ranges from 47-52 MJ/kg [17] while biomass is in the range of 8-25 MJ/kg [25], [26]. In addition to this, there is a negative correlation between the heating values of biomass and the moisture content present, as shown in Figure 2.2. This is because some of the combustion heat is used to evaporate the moisture content in the fuel [18].

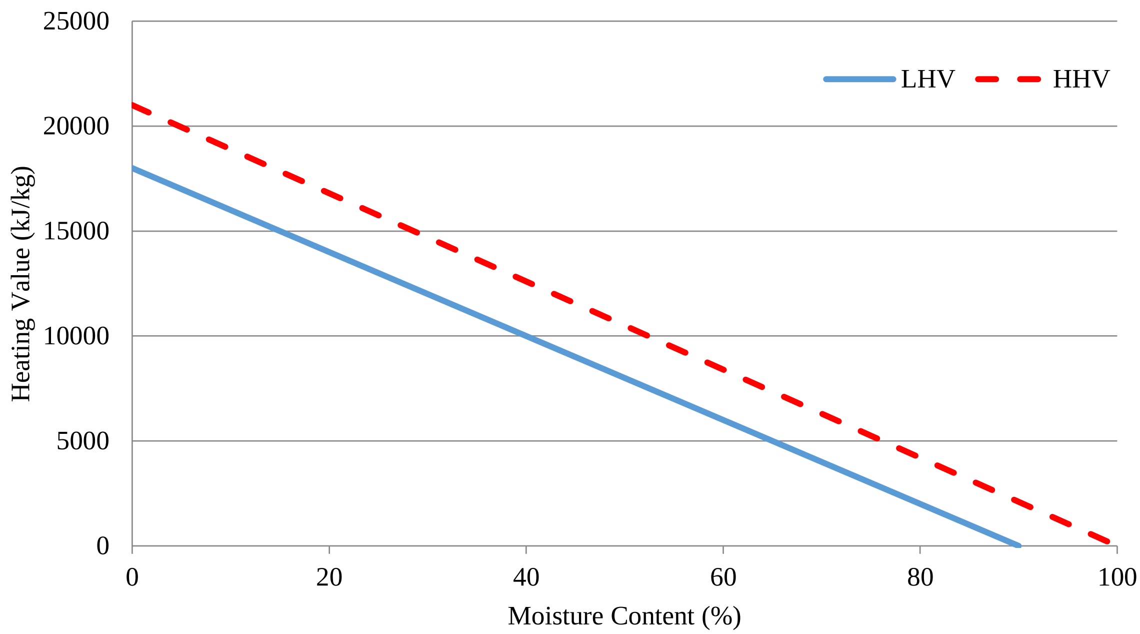

Figure 2.2. Lower heating values (LHV) and higher heating values (HHV) of biomass versus moisture content [27].

The primary biomass fuel source for the UI is western red cedar which is obtained from the local logging industry. Specifically, the biomass fuel is in the form of wood chips and slash, which is the excess waste after the lumber has been processed. Wood chip sizes range from 1-15cm and has a negligible impact for the purpose of this analysis. The proximate and ultimate analyses of the woody material are listed in Table 2.1. Heating values have previously been calculated experimentally and range between 20.22-20.97 MJ/kg on a bone dry basis [28].

Table 2.1. Chemical composition of wood chips based on proximate and ultimate analyses [29].

Proximate analysis					
VM	FC	M	A	Sum	
77.5	14.5	7.8	0.2	100	
Ultimate Analysis					
C	O	H	N	S	Sum
49.6	44.1	6.1	0.1	0.06	99.98

Figure 2.3. Wood chip fuel comprised of western red cedar. Photo courtesy of UI district energy plant.

At the UI the moisture content of the wood chips received ranges from 6% by weight to nearly 60% during adverse weather conditions, with a yearly average of 30%. Since the moisture content in biomass has a direct impact on the heating value, steps are taken to reduce the moisture content before combustion. A storage facility located on campus uses natural convection from wind currents to reduce the moisture content approximately 10% before being sent to the energy plant. This increases the efficiency of the combustion process.

2.3.2 Energy Analysis

The boilers are not insulated at the energy plant, however for ease of calculations, the boilers are assumed to be insulated, with the heat dissipation to the surrounding environment being neglected. In addition to this, there is no work done either to or by the boilers and the potential and kinetic energy changes are negligible. If the mass flow rates into and out of the boilers, as well as the net energy change in the system, E_{sys}, is assumed to be constant, the general first law balance of each boiler can be written at steady state as:

$$\dot{Q}_{in} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} = \frac{dE_{sys}}{dt} = 0 \qquad (2.1)$$

With the campus load requirements known the amount of energy needed can be determined. The thermal efficiency of each boiler is a function of the energy output required and the energy input provided by the fuel source:

$$\eta = \frac{\dot{Q}_{in}}{\dot{m}_{fuel} HV_{fuel}} \tag{2.2}$$

2.3.3 Exergy Analysis

An exergy analysis is a useful tool in determining the sustainability and environmental impact of a process [30]. An exergy efficiency of 100% would represent a completely sustainable, reversible process while an efficiency of 0% would correspond to the opposite, since the resource is being consumed, but nothing useful is being accomplished [31].

$$\psi = h_{out} - h_0 - T_0(s_{out} - s_0) \tag{2.3}$$

The exergy rate provided by the fuel input to the furnace can be approximated as the average higher heating value of the wood chip fuel multiplied by the mass flow rate:

$$\dot{X}_{fuel} = \dot{m}_{fuel} HHV_{fuel} \tag{2.4}$$

Since exergy is always destroyed in real world processes due to inherent irreversibilities an exergy balance is performed allowing for the exergy destruction rates, which are useful for optimizing a thermodynamic system, to be calculated:

$$\dot{X}_{in} + \dot{m}_{in}(\psi_{in} - \psi_{out}) - \dot{X}_{des} = \frac{dX_{sys}}{dt} = 0 \tag{2.5}$$

The exergy efficiency is defined in general terms as:

$$\eta_X = \frac{product\ exergy\ output}{exergy\ input} \tag{2.6}$$

Which can be rewritten as follows for the boilers:

$$\eta_X = \dot{m}_{in}\left(\frac{\psi_{out} - \psi_{in}}{\dot{X}_{fuel}}\right) \tag{2.7}$$

2.3.4 Combustion

Each boiler at the UI energy plant is monitored to ensure that 2-5% excess oxygen is present in the exhaust so that a stoichiometric reaction takes place during combustion. This is done using computer control systems to optimize both emissions and thermal efficiency. Adding more air than needed for complete combustion prevents the formation of harmful emissions such as carbon monoxide (CO) and any unburned hydrocarbons from the fuel [32]. Too much additional air however will reduce the thermal efficiency. For this analysis the oxygen content in the exhaust will be assumed to be 3% for both biomass and natural gas fuels.

The chemical composition of wood varies greatly between species and is usually defined on a dry weight percentage as opposed to a chemical formula. For the purpose of combustion in this study, wood is defined as having the chemical composition shown in Figure 2.4, comprising primarily of carbon, oxygen, hydrogen, and other trace components such as nitrogen and sulfur [9], [25], [29]. Natural gas is approximated as methane with a chemical formula of CH_4.

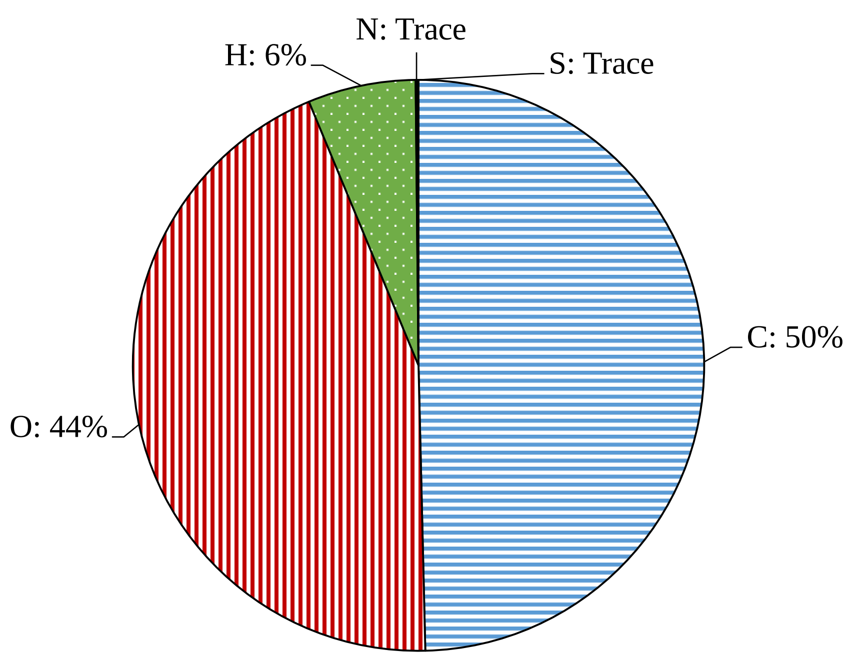

Figure 2.4. Chemical composition of bone dry wood by weight.

To begin the analysis, first a chemical balance is performed on the stoichiometric combustion of fuel in dry air to determine the stoichiometric combustion coefficient, ν_0 [24]:

$$C_\alpha H_\beta S_\gamma O_\delta N_\varepsilon + v_0(O_2 + 3.76N_2) \rightarrow v_1 CO_2 + v_2 H_2O + v_3 SO_2 + v_4 N_2 \quad (2.8)$$

With the atomic balances resulting in:

C: $\alpha = v_1$

H: $\beta = 2v_2$

S: $\gamma = v_3$

O: $\delta + 2v_0 = 2v_1 + v_2 + 2v_3$

N: $\varepsilon + 2 * (3.76)v_0 = 2v_4$

To account for the excess air provided to the process, an additional balance is performed for the lean combustion of fuel in dry air using ν_0 found in equation 2.8:

$$C_\alpha H_\beta S_\gamma O_\delta N_\varepsilon + \xi_0(O_2 + 3.76N_2) \rightarrow \xi_1 CO_2 + \xi_2 H_2O + \xi_3 SO_2 + \xi_4 O_2 + \xi_5 N_2 \quad (2.9)$$

This results in the following atomic balances, with ξ_0 being the excess air coefficient:

$\xi_0 = v_0(PTA)$

C: $\alpha = \xi_1$

H: $\beta = 2\xi_2$

S: $\gamma = \xi_3$

O: $\delta + 2\xi_0 = 2\xi_1 + \xi_2 + 2\xi_3 + 2\xi_4$

N: $\varepsilon + 2 * (3.76)v_0 = 2\xi_5$

The total number of moles of combustion products is defined as:

$$n_p = \xi_1 + \xi_2 + \xi_3 + \xi_4 + \xi_5 \quad (2.10)$$

The mole fractions are then computed with equations 2.11-2.15. These give the final composition of the combustion products on a volumetric basis, so that the biomass and natural gas fuels can be compared.

$$y_{CO_2} = \frac{\xi_1}{n_p} \quad (2.11)$$

$$y_{H_2O} = \frac{\xi_2}{n_p} \quad (2.12)$$

$$y_{SO_2} = \frac{\xi_3}{n_p} \quad (2.13)$$

$$y_{O_2} = \frac{\xi_4}{n_p} \quad (2.14)$$

$$y_{N_2} = \frac{\xi_5}{n_p} \quad (2.15)$$

Finally, the air fuel ratios can be determined with the following set of equations where M_{air} is the molecular weight of dry air and M_{fuel} is the molecular weight of the selected fuel.

$$AF_{mol} = \frac{moles\ of\ air}{moles\ of\ fuel}$$

$$AF_{mol,act} = \frac{\xi_0(1 + 3.76)}{1} = 4.76\xi_0 \quad (2.16)$$

$$AF = AF_{mol,act}\left(\frac{M_{air}}{M_{fuel}}\right) \quad (2.17)$$

2.4 Case Study: Boilers in the University of Idaho Energy Plant

2.4.1 History

The district energy system at UI was built in 1926 and originally provided heat to the main campus with a combination of three lump coal fired boilers. In 1940 an additional coal fired boiler was installed to handle increasing campus load requirements. Over time the configuration in the energy plant changed to improve efficiency, starting with the switch to pulverized coal in 1948 for the newest boiler, then eventually natural gas boilers replacing two of the original lump coal boilers in 1963 and 1975. The last shipment of coal arrived at the UI energy plant in 1985, as the pulverized coal boiler was converted to burn natural gas and the final lump coal boiler was decommissioned. The timeline for the evolution of the energy plant is shown in Figure 2.5.

To control increasing air pollution in the U.S., laws such as the Clean Air Act of 1963 were put into place to monitor and reduce the output of greenhouse gases. Over time the regulations became stricter and the logging industry was no longer able to burn the waste generated at their lumber mills. The new laws would require mills to truck the waste to landfills for burial if they wanted to meet standards, which was cost prohibitive.

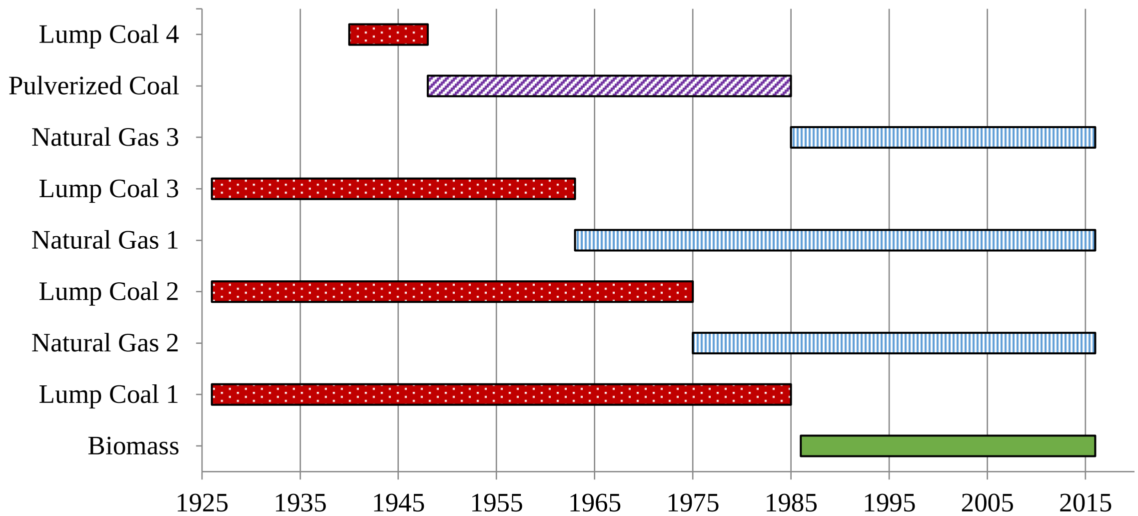

Figure 2.5. Timeline of boiler evolution at the UI district energy plant from 1926 to 2016.

In an effort to reduce greenhouse gas emissions and become more environmentally friendly an agreement was made between UI and local logging companies where the companies invested in the installation of a new boiler that would be fueled by the wasted wood chips generated from logging. This would supply the university with a clean, sustainable fuel source as opposed to the lump coal still in use while providing a means for lumber mills to remove waste in an environmentally friendly manner.

In 1986 the biomass boiler came online, along with a similar design at the University of Central Michigan. Biomass boilers at this scale were unheard of at the time and this was to be a test on the feasibility of the concept. Today the biomass boiler provides almost all of the steam required throughout the year, with the natural gas boilers supplementing the rest and kept as backups.

2.4.2 Sourcing Wood Chips

The lumber mills in the area that provide the wood chips to the UI energy plant generate a continuous stream of waste that needs to be burned off. This means that UI needs to be able to accept wood chips on a steady basis, even if campus load requirements are low, such as during the summer months. The storage facility on campus allows for the excess wood chips to be stockpiled for use during peak load times, in addition to reducing the moisture content.

When the biomass boiler was first installed, the UI wasn't charged for the wood chips for several years, because there was no demand for them and it solved the waste problems the lumber mills had. This large supply of free fuel was financially beneficial for the university. Eventually the paper industry grew and was willing to buy the wood chips, resulting in competition for the waste. Despite eventually needing to purchase wood chip fuel, costs are still competitive with natural gas piped in from sources in Canada, Washington State, and Oregon thanks to their proximity.

2.4.3 Equipment

Each boiler at the UI energy plant has a different configuration to improve performance, as shown in Table 2.2. These differences stem from generational differences in boiler technology and the load placed on each boiler. Since the biomass boiler supplies most of the steam required on campus, efforts have been made to maximize its efficiency as much as possible.

Table 2.2. Additional equipment installed on individual boilers.

Component	Biomass	NG 1	NG 2	NG 3
Multi-cone cyclonic separator	X			
Economizer	X	X		
Air Pre-heater	X			X
New (<2 yrs) Burner Package				X

2.4.4 Biomass Boiler Exhaust Measurements

To ensure that greenhouse gas emissions levels are within EPA regulations tests are conducted periodically by an outside party. On November 19, 2013 Bison Engineering Inc.

personnel tested the exhaust stream of the biomass fueled boiler to determine the moisture content, oxygen, carbon dioxide levels, and particulate emissions following EPA methods 1 through 5, described in Title 40, Code of Federal Regulations (CFR), Part 60, Appendix A [33].

Measurements were taken of the average velocity, temperature, static pressure, and cross-sectional area of the testing location to calculate the volumetric flow rate. Samples were then collected to be analyzed using these measurements at the Bison laboratory.

2.5 Analysis

Generally, only one boiler is run at a time at the UI energy plant to meet the energy requirements of campus. The biomass boiler operates throughout the year and is only shut down for maintenance purposes. Additional boilers are brought online during peak load times in the winter. As such measurement data is not available for the three natural gas boilers. To account for this and compare the exergetic performance of the boilers, a baseline is created using the average thermal efficiencies of each boiler and the flow conditions presented in Table 2.3. Rearranging equation 2.1 while including yearly steam production data allows for the load requirements to be determined at the given flow conditions, shown in equation 2.18. This is the load that each boiler, represented in Figure 2.6, must be able to meet. With yearly steam requirements known and kept constant, each boiler is compared by its ability to meet the same full load. Using their average thermal efficiencies allows for a comparison despite each boiler having a different equipment configuration.

$$\dot{Q}_{load} + \dot{m}_{water} h_{water} - \dot{m}_{steam} h_{steam} = 0 \tag{2.18}$$

Table 2.3. Water and steam flow conditions for boilers.

Point	$\dot{m}$ (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg-K)	ψ_f (kJ/kg)
Reference	-	294.2	91.7	88.18	0.3107	-
Inlet (water)	3.878	294.2	10.21	88.1	0.3107	0
Outlet (steam)	3.878	454.5	10.21	2778	6.573	848

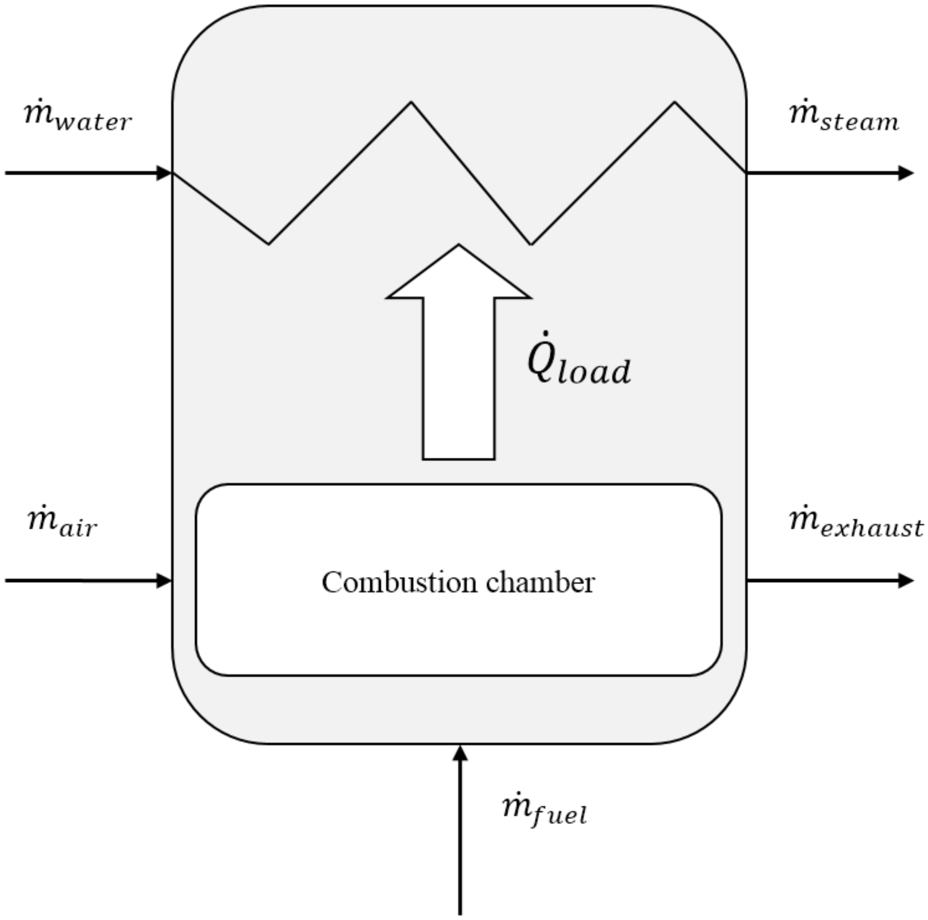

Figure 2.6. Flow conditions through each boiler.

Combining the load requirement with equations 2.2 and 2.4 provides the mass flow rate of fuel required as well as the exergy content of the fuel, shown in Table 2.4. Equating the exergy content of the fuel to the exergy input of equation 2.5 allows for exergy destruction rates to be found.

Applying equation 2.8 for the biomass boiler to determine the stoichiometric biomass combustion products is as follows:

$$C_{0.496}H_{0.061}S_{0.0006}O_{0.441}N_{0.001} + 0.2914(O_2 + 3.76N_2) \rightarrow 0.496CO_2 + 0.0305H_2O + 0.0006SO_2 + 1.096N_2 \quad (2.19)$$

Table 2.4. Parameters found using equations 2.2 and 2.4.

Boiler	$\dot{Q}_{load}$ (kW)	$\dot{m}_{fuel}$ (kg/s)	HV_{fuel} (kJ/kg)	$\dot{X}_{fuel}$ (kW)
Biomass	10432	0.6663	20600	13727
NG 1	10432	0.247	49680	12273
NG 2	10432	0.2695	49680	13375
NG 3	10432	0.247	49680	12273

Taking the results from equation 2.19 and solving equations 2.9-2.17 simultaneously results in the parameters shown in Table 2.5 to determine the molar fractions of the combustion products. The process is then repeated for the natural gas boilers (NG1, NG2, and NG3), with equation 2.20 showing the stoichiometric chemical balance.

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow 1CO_2 + 2H_2O + 7.52N_2 \qquad (2.20)$$

Table 2.5. Combustion parameters for each fuel type at 3% excess oxygen.

Parameter	Biomass (bone dry)	Natural Gas
AF	4.356	20.36
AF_{mol}	1.971	11.27
M_{air} (kg/kmol)	28.97	28.97
M_{fuel} (kg/kmol)	13.11	16.04
$M_{exhaust}$ (kg/kmol)	31.68	27.81
PTA	1.421	1.184
v_0	0.2914	2
v_1	0.496	1
v_2	0.0305	2
v_3	0.0006	0
v_4	1.096	7.52
ξ_0	0.4141	2.368
ξ_1	0.496	1
ξ_2	0.0305	2
ξ_3	0.0006	0
ξ_4	0.1227	0.3682
ξ_5	1.557	8.904
n_p	2.207	12.27
y_{CO2}	22.47	8.148
y_{H2O}	1.382	16.3
y_{N2}	70.56	72.56
y_{O2}	5.56	3
y_{SO2}	0.02718	0

2.6 Results and Discussion

2.6.1 Efficiencies

The thermal and exergy efficiencies of each boiler can be seen in Table 2.6. It is expected that the thermal and exergy efficiency values for the biomass boiler are lower than the natural gas boilers due to the lower heating value of the fuel, despite having equipment installed to improve efficiency. The natural gas boiler with no additional equipment installed has a lower efficiency compared to the others, which provides a baseline for comparing the potential benefits of upgrading equipment.

Table 2.6. Efficiencies of boilers when steam temperature leaving boiler is 455K.

Boiler	Energy	Exergy
Biomass	76%	24%
NG 1	85%	27%
NG 2	78%	25%
NG 3	85%	27%

The efficiencies of each boiler are of some interest. NG boiler 3 was originally built in 1940 and yet has comparable performance with the newer boilers due to the equipment upgrades introduced throughout its life. NG boiler 2, however, still uses 1960s technology with no upgrades and has a noticeably reduced thermal efficiency compared to the other NG boilers. While the efficiency of the biomass boiler is lower, it is utilizing a waste stream from another industry and is more environmentally friendly than the other boilers. This low efficiency indicates that further study is needed to enhance the efficiency of the boiler.

The exergy content of the fuel fluctuates due to the different mass flow rates of fuel required for each boiler. The lower thermal efficiencies of the biomass and second natural gas boiler correlate to increased fuel requirements for the same amount of steam produced, and thus higher exergy content and destruction rates, which are shown in Table 2.7.

Table 2.7. Mass and exergy flow rates of fuel per boiler.

Boiler	Fuel (kg/s)	Exergy (kW)	Exergy Destruction (kW)
Biomass	0.6663	13727	10438
NG 1	0.247	12273	8985
NG 2	0.2692	13375	10086
NG 3	0.247	12273	8985

2.6.2 Combustion Results

The mathematical model generates the composition of the emissions products from each fuel source, shown in Table 2.8, as a result of the combustion process, with ratios present in Figure 2.7 and Figure 2.8. Since excess air is provided to the combustion process, no CO is produced by either fuel and all the fuel is completely consumed. The biomass fuel is analyzed on a bone dry basis with no water present, resulting in reduced water vapor in the emissions products and increased CO_2 by volume. Due to the high carbon content of the wood chips, CO_2 output is higher than that of natural gas. Again, it is important to note that the CO_2 being released by the biomass, while being emitted at a higher rate than natural gas, does not result in a net increase in greenhouse gases since it was originally absorbed during its growth.

Table 2.8. Combustion products from each fuel source based on the combustion analysis at 3% excess air.

Product	Biomass	Natural Gas
CO_2	26.2%	8.15%
H_2O	1.61%	16.3%
N_2	69.16%	72.56%
O_2	3.0%	3.0%
SO_2	0.03%	N/A

When the fuel is burned completely all of the carbon content is released in the form of CO_2. If complete combustion was not reached, some of the unburned biomass fuel would have remained in the left-over ash, and thus some of the carbon content would have remained instead of being released to the atmosphere. In the event of incomplete combustion of the natural gas, CH_4 would have been released. Nitrogen gas does not react during combustion and so passes through the process.

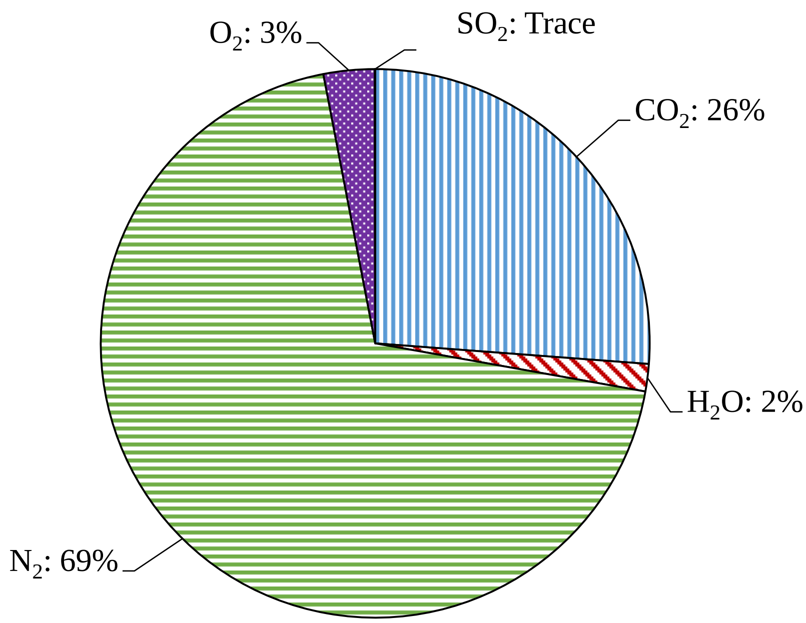

Figure 2.7. Molar composition of bone dry biomass combustion products by volume using the combustion model.

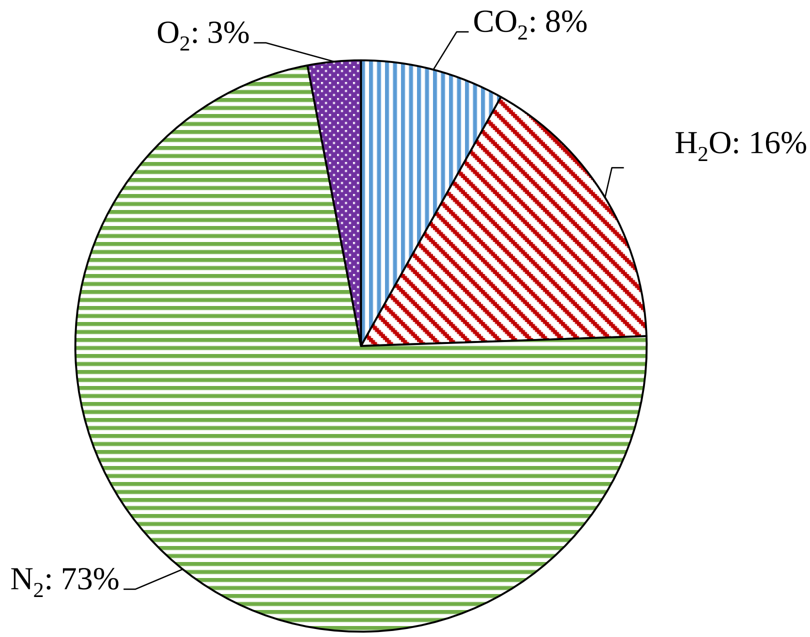

Figure 2.8. Molar composition of natural gas combustion products by volume.

2.6.3 Biomass Boiler Exhaust Test Results

Three separate tests were conducted by Bison Engineering, each lasting 60 minutes, with the results shown in Table 2.9. The composition of the emissions products was determined at the Bison laboratory with the samples taken. The averaged emissions products by volume are shown in Figure 2.9. The average moisture content of the wood fuel during testing was measured to be 33% of the total weight.

The large percentage of moisture in the fuel results in reduced CO_2 output by volume. While this may appear to be beneficial, it ultimately results in increased fuel consumption by the boiler. The combustion of biomass releases particulates beyond the scope of this study, however it should be considered when investigating fuel consumption. Decreasing the moisture content would result in increased particulates in the exhaust. This indicates the possibility of a tradeoff between the need to increase efficiency by reducing moisture content and keeping particulate emissions within acceptable levels by allowing some moisture content to be present in the fuel.

Table 2.9. Biomass boiler exhaust stack measurements.

Parameter	Test 1	Test 2	Test 3
Pressure (kPa)	91.74	91.74	91.74
Temperature (C)	184	173	176
Velocity (m/s)	12.8	11.64	11.52
Flow (m^3/s)	14.96	13.59	13.46
CO_2 (%)	14	14	14
H_2O (%)	13.21	15.38	14.42
O_2 (%)	5.74	5.6	5.45

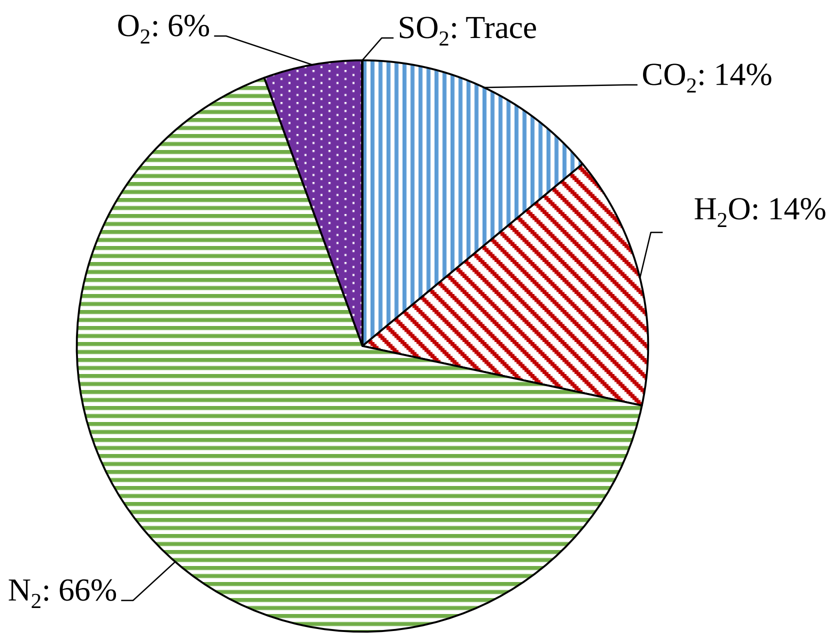

Figure 2.9. Molar composition of actual biomass combustion products by volume.

2.6.4 Fuel Cost Comparison

Campus load requirements fluctuate between summer and winter seasons, as heating and cooling needs change and the student body leaves for the academic breaks, leaving many buildings unoccupied. During the warmer summer months, the heating requirements are reduced substantially, though not completely eliminated. It would be uneconomical for the biomass boiler to be in operation during these months because of the reduced thermal efficiency associated with the partial loading. However, shutting down the biomass boiler and switching to the natural gas boilers would increase operating costs due to the higher cost of natural gas compared to wood chips. To allow the biomass boiler to be in operation throughout the year and maximize fuel savings an absorption chiller is located inside of the steam plant. The absorption chiller is part of the district chilled water system also located on campus to provide process equipment cooling and environmental room conditioning. This brings the load requirements on the steam plant up to levels that are suitable for the biomass boiler to continue operation, resulting in further savings compared to natural gas or other forms of satisfying cooling needs.

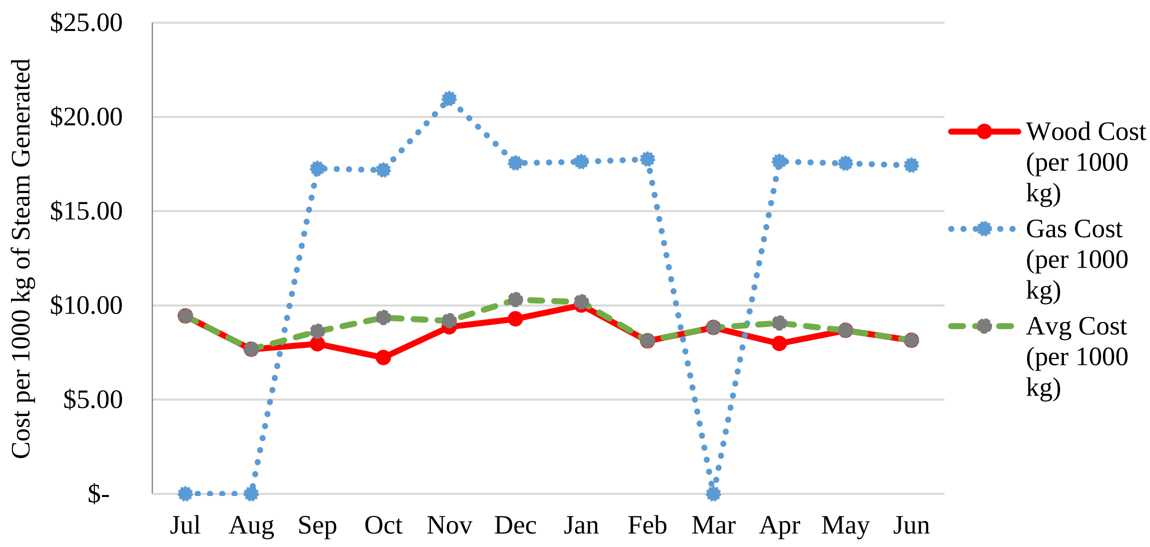

Figure 2.10. Monthly costs of steam produced for FY15.

Figure 2.10 shows that both natural gas and wood chip fuel costs are generally stable throughout the year, with a slight increase for wood costs during the winter months, when demand is high. The cost for natural gas drops to zero in Figure 2.10 when no natural gas is used during that month. In 2015, the average cost per bone dry ton (BTD) of wood chips was $51.00, while the cost for natural gas averaged $6.00 per deca-therm. Fuel consumption and steam production is monitored daily by the UI energy plant, with the monthly totals shown in Table 2.10 for the 2015 fiscal year.

Table 2.10. Monthly fuel and steam data for FY15. Data provided by UI district energy plant.

Month	Steam by Wood (1000 kg)	Wood Cost (per 1000 kg)	Steam by Gas (1000 kg)	Gas Cost (per 1000 kg)	Total Steam (1000 kg)	Avg Cost (per 1000 kg)
Jul	8376.02	$ 9.44	0.00	$ -	8376.02	$ 9.44
Aug	8460.41	$ 7.67	0.00	$ -	8460.41	$ 7.67
Sep	7237.62	$ 7.96	547.94	$ 17.26	7785.56	$ 8.61
Oct	7949.84	$ 7.23	2155.63	$ 17.17	10105.47	$ 9.35
Nov	12083.49	$ 8.86	331.71	$ 20.97	12415.20	$ 9.19
Dec	11734.90	$ 9.28	1648.49	$ 17.55	13383.39	$ 10.30
Jan	12746.41	$ 10.01	296.83	$ 17.61	13043.25	$ 10.18
Feb	10264.81	$ 8.11	19.07	$ 17.75	10283.88	$ 8.13
Mar	10384.56	$ 8.82	0.00	$ -	10384.56	$ 8.82
Apr	9340.39	$ 7.98	1180.35	$ 17.64	10520.74	$ 9.06
May	9973.15	$ 8.66	6.85	$ 17.53	9980.00	$ 8.67
Jun	7547.79	$ 8.14	1.48	$ 17.44	7549.26	$ 8.14
Total	116099.39	$ 8.61	6188.36	$ 17.60	122287.75	$ 9.07
Overall %	95%		5%			

Over 122 million kg of steam was produced by the energy plant in 2015 with biomass supplying 95% of the total amount. The cost per 1000 kg of steam produced using wood chips is over 63% lower than that of natural gas, resulting in substantial savings annually. To produce all of the steam required using natural gas without any biomass fuel consumption would cost over $2.1 million as opposed to $1.1 million using biomass, resulting in over $1.0 million in annual savings for the university. It is for this reason that the biomass boiler is used to provide as much steam as possible to reduce costs. Natural gas is used during excessive loads or during routine maintenance of the biomass boiler and provides a reliable supply of backup fuel.

The financial savings from the use of biomass fuel are the result of a combination of factors. UI's close proximity to a reliable fuel source minimizes transportation costs which is a significant factor. The type of biomass fuel also plays a key role, as sources such as industrial waste wood might require more emissions equipment to capture possible toxins. Some parts of the world, such as Europe, have a high demand for biomass and as such fuel costs can hinder the feasibility of such systems. Some systems, for example large scale power plants, might require more energy than biomass fuel can provide due to the lower average heating value. This highlights the importance of geographical location and investigating all potential energy sources when developing new energy systems.

2.7 Conclusions

An investigation, based on the second law of exergy, of the boilers at the UI district energy plant has been conducted. Four different boilers, each with different configurations, are evaluated and the thermal and exergy efficiency of each is compared. Fuel sources have also been investigated to determine impacts both economic and environmental in the terms of CO_2 output and its contribution to climate change.

The reduced heating values of the biomass fuel results in reduced thermal and exergy efficiencies compared to natural gas while at the same time providing significant fuel cost savings and increasing the sustainability footprint of the campus. Thermal efficiencies vary from 76% to 85% while the exergy efficiency is relatively low for all the boilers, ranging from 24% to 27%. Much of this is due to the large amount of exergy destroyed during the combustion process, which is an unavoidable characteristic of combusting fuel. Additionally, a substantial amount of the exergy flow is exhausted out to the atmosphere instead of being utilized. This is because not all of the heat produced can be transferred to the water to produce steam [30]. Further investigations into individual boilers while taking into account the equipment installed to improve efficiency can reveal their impacts on exergy efficiency. It is expected that the exergy efficiency will increase as the input flow temperatures increase, which would be reflected when components such as the economizer are modeled.

Using biomass as a fuel source produces more CO_2 during the combustion process compared to natural gas. That same volume of CO_2 was absorbed by the trees during their lifecycle however, and thus does not generate a net change in the amount present in the atmosphere, unlike the fossil fuel counterpart. Because of the close proximity of a biomass fuel source to the UI campus, transportation costs are reduced. This minimizes the ancillary emissions created by regular shipments of wood chips delivered by trucks. Utilizing biomass as a fuel source is generally considered to be an environmentally friendly means to operate boilers. However, if the fuel cannot be sourced locally the transportation costs, both economically and environmentally, could be costlier than fuels such as natural gas.

The substantial savings in fuel costs, coupled with the carbon neutral quality of the fuel source show the potential advantages of biomass fuel in boilers. It is a sustainable fuel that can offset the damage caused by burning fossil fuels. It is also versatile enough that coal fueled boilers, for example, can take advantage of it by co-firing with biomass, resulting in lower operating costs and cleaner emissions with modest capital investment. The district energy plant at the UI demonstrates that large scale biomass combustion can perform as well as fossil fuels at less cost and without producing harmful greenhouse gases.

The low exergy efficiency of the boilers indicates the need for additional study for potential for future improvements to the energy plant. Expanding the scope of this analysis to include the full steam cycle may provide insight as to which components or processes contribute the most to exergy destruction. Modifying the current plant by installing a steam turbine and generator to create a cogeneration cycle to produce electricity would increase the exergy efficiency of the energy plant. An engineering economic analysis would need to be conducted to determine the feasibility of such a modification.

Chapter 3: Exergy Approach for Advancing Sustainability of a Biomass Boiler

Forthcoming in *The International Journal of Exergy*

3.1 Abstract

An exergy analysis of the district energy plant at University of Idaho, Moscow, Idaho, USA is presented. Exergy flows through the components of the steam cycle, specifically through the biomass boiler, are quantified to identify major sources of exergy destruction in the district heating system. A mathematical model is developed to determine the sources of exergy destruction using measurements taken at each state of the steam cycle. It is found that the largest sources of exergy destruction occur in the boiler and furnace at 35% and 33% of the overall exergy losses, respectively, followed by the heating equipment on campus at 5.7% and the pressure reducing valve (PRV) at 3.5%. Parametric studies reveal that decreasing steam pressure levels through the boiler to reduce exergy destruction in the PRV result in increased exergy destruction rates in the boiler. Increasing boiler steam pressure levels instead reduces exergy destruction in the boiler, but has negligible effects on the overall exergy efficiency of the complete cycle. This indicates that the PRV is limiting potential improvements in the boiler exergy efficiency.

3.2 Introduction

In achieving sustainable development, it is important for a society to utilize resources that cause little or no environmental impacts [34]. For a system to be completely sustainable it must also be reversible, however the second law of thermodynamics indicates that all real processes are inherently irreversible and thus impact the environment. While ultimately no activity is perfectly sustainable, it is possible to approach sustainability on a timespan that can be benefit both current and future generations [35].

One of the most important factors in accomplishing this is the responsible and efficient use of sustainable energy resources [36]. Fossil fuels such as oil, coal, and natural gas constitute the largest sources of energy in the modern world and due to their nature release greenhouse gases (GHGs) during the combustion process. While the primary GHGs, such as carbon dioxide (CO_2), occur naturally, concentrations of them in the atmosphere since the pre-industrial era have increased substantially due to human activity [37]. Fossil fuels are also finite in the time span of approaching sustainable development and will eventually need to be replaced with renewable energy sources. This is where alternative energy sources such as solar, wind, tidal, and biomass can lead to a more sustainable society where impacts on the environment are greatly mitigated. It has been suggested by Omer that reducing energy consumption and exploiting renewable energy technology in buildings to produce heating, cooling, and other needs can have significant impact on GHG generation [38].

Investigations into district energy (DE) systems have been shown to offer the potential for reductions in GHG emissions [12], [39]. This can be accomplished by utilizing energy sources that reduce net carbon emissions to the environment, such as biomass fuels, and replacing heating and cooling equipment in individual buildings with higher efficiency equipment at a central location [11]. District energy systems produce low pressure steam, hot water, and/or chilled water for use in multiple buildings. Using a centralized production plant and underground piping networks allows for thermal energy to be transported for both heating and cooling needs [16]. Rezaie et al. have demonstrated the economic costs associated with CO_2 emissions through carbon taxes on the use of fossil fuels as opposed to potential credits for the use of renewable energy sources [14], [15]. Gong et al. have suggested that locally sourced energy sources, particularly ones with low exergy content, should be utilized in district heating to provide low quality space heating and domestic hot water [40], [41].

It has been suggested by Szargut et al. that to best realize increased efficiency by utilizing energy resources while reducing their impact on the environment, exergy methods should be considered [42]. The development of exergy and its applications has been outlined by Sciubba and Wall [43]. It has also been shown by Sciubba that accounting for exergy input and destruction rates can provide a means to assess the efficiency of the resources used [44]. Exergy is commonly considered to be the maximum work that can be obtained from a system within a specified reference environment, or the quality of the energy source [5]. Exergy is not a conserved quantity, like energy, and an exergy balance can account for inputs, losses, and wastes of a process [45]. Extensive links between energy, exergy, and sustainable development have been made by Dincer and Rosen [3], [46]–[49], which suggests that exergy might provide a basis for measuring the potential an energy source has of impacting the environment. Caliskan conducted energy, exergy, sustainability, and economic analyses when investigating the choice of solar, biomass, and electricity to heat a building [50]. It was found that solar energy had the best results for building heating applications, followed by biomass and that their use should be encouraged.

The main University of Idaho (UI) campus in Moscow, Idaho, USA utilizes a DE system for heating and cooling needs. The plant has undergone many changes since its opening in 1926. Currently, a biomass fueled boiler at the energy plant provides steam to buildings on campus for heating. Cooling needs are met using a thermal energy storage (TES) system, coupled with a 2100kW (600 refrigeration ton), single effect, lithium bromide absorption chiller using steam produced at the energy plant as well as electric chillers [51]. Previous research was conducted to investigate the exergy efficiency of the biomass and natural gas boilers at the energy plant [52]. It was found that the biomass boiler has a lower energy and exergy efficiency, despite additional equipment to improve performance. The use of biomass, in the form of wood chips, does result in significant economic savings over the use of natural gas however. A similar study was conducted by Terhan, et al. to determine sources of exergy losses in natural gas boilers [53]. They determined that that 17% of energy and 6% of exergy losses in a boiler are through the flue gas, indicating the importance of breaking down exergy flows through the entire boiler to locate exergy losses. Gürtük, et al. investigated sources of exergy destruction in a circulating fluidized bed boiler CHP system [54]. They also determined that the exergy efficiency of the boiler was low when compared to other boilers. Da Silva et al. took an exergy approach when assessing the efficiency of steam generators, where it was shown that while most energy losses were through the flue gas, exergy losses were greater during combustion and heat transfer within the boiler itself [55]. Similar behavior was shown by Adibhatla et al. when integrated a solar field with an existing coal fired steam plant [56], however exergy losses were even higher in the solar field due to the large temperature differences between surfaces.

The purpose of this paper to quantify the primary exergy losses in the UI district energy plant. It has been argued that exergy can be used as a measure of waste emissions and potential for causing environmental harm [57], [58]. Boilers are critical for any district energy system and are a significant consumer of energy in the U.S. [23]. As such, it is important that they are utilized in the most efficient manner possible to reduce fuel consumption and minimize their environmental impact. The use of biomass fuel at UI reduces the carbon footprint of the energy plant, but boiler performance is lower than that expected compared to the natural gas boilers. The previous research has shown that older generations of boilers can have comparable performance with newer boilers after modification. Quantifying exergy losses in the system provide the opportunity to identify where modifications would have the largest impact on the performance of the wood chip boiler.

3.3 Methodology

A thermodynamic approach is taken in the analysis of the case study considered here. To facilitate calculations and ensure accuracy, Engineering Equation Solver (EES) V9.911 was used throughout the study.

3.3.1 Scope Definition

The scope of this assessment evolves around the steam cycle through the biomass boiler at the UI energy plant. The irreversibility, or exergy loss, of the steam cycle is the criterion applied and identifies which components account for the exergy losses associated with using natural resources [59]. For ease of calculation, the equipment and process for delivering wood chips to the furnace has been neglected. Wood chip fuel is sourced from different lumber mills located within the inland northwest region of the US, each with their own methods of operation; thus, each has its own life cycle for wood chips from growth, harvesting, processing, and transportation and would be more appropriately assessed separately. The emphasis and scope of this assessment is solely on the production of steam at the energy plant for use in the district heating and cooling system on campus. Sixty-two buildings on campus make use of the process steam for heating needs, as do significant portions of the walkways and roads that are heated to prevent ice buildup in the winter. Consumer use, pipe insulation material, pumping requirements, and many other factors cannot be neglected and would be needed for an accurate model of the network [60]. Due to this complexity, the steam network as it is used on campus is easier dealt with in a separate assessment. Therefore, as the conditions leaving and entering the plant are known, the campus is modeled as a single component in the steam cycle.

A 600-ton absorption chiller accounts for a significant portion of the steam production requirements during the summer months. The absorption chiller does not supply cooling needs for the campus directly but instead, as part of the DE system on campus, it is used to provide chilled water to the TES tank located separately from the energy plant. The TES tank provides cooling to most of campus during the day, when operating individual chillers would be less efficient. By integrating the energy plant with the TES into one district heating and cooling network, the load on the absorption chiller is relatively constant throughout the day, reducing the need for cycling. Steam requirements for the chiller are less during the day, when the TES is operating, and increase at night when the efficiency of the chiller increases with the cooler ambient temperatures. The absorption chiller is included in the analysis as a cooling load, however the TES tank and associated pumping is neglected. Additional electric chillers are also located in the energy plant, however as they do not utilize any of the steam produced they are not included in this study.

3.3.2 Exergy

For a system at steady state, the mass balance can be written as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3.1}$$

The energy balance can be written on a rate basis as:

$$\begin{gathered}\sum\left(\dot{Q}+\dot{W}\right)_{in}-\sum\left(\dot{Q}+\dot{W}\right)_{out}+\sum \dot{m}_{in}\left(\mathrm{h}-\frac{V^2}{2}+gz\right)_{in}- \\ \sum \dot{m}_{out}\left(\mathrm{h}-\frac{V^2}{2}+gz\right)_{out}=\frac{dE_{sys}}{dt}=0\end{gathered} \tag{3.2}$$

The thermal (or energy) efficiency of the cycle considered here, which is a measure of how much useful energy is produced from a given input of fuel, can be expressed as follows:

$$\eta_{energy} = \frac{product\ energy\ output}{energy\ input} \tag{3.3}$$

Which can be written for the cycle as:

$$\eta_{energy} = \frac{\dot{Q}_{campus} + \dot{Q}_{chiller}}{\dot{m}_{fuel} HHV_{fuel} + \sum \dot{W}_{pumps} + \sum \dot{W}_{fans}} \quad (3.4)$$

To begin the exergy analysis, the reference, or “dead”, state is defined. Because useable work requires a difference between the states of the system and the surrounding environment, exergy is always evaluated with respect to a dead state [61]. The reference state is often determined by the ambient weather conditions at the time of the analysis. Since exergy is always destroyed in real processes due to inherent irreversibilities, an exergy balance of a general system can be written as:

$$Exergy\ input - Exergy\ output - Exergy\ destroyed = Exergy\ increase \quad (3.5)$$

The specific physical exergy for each flow state, which is a measure of the maximum work that can be generated from a flow while interacting with the dead state, can be expressed as:

$$\psi = h_{out} - h_0 - T_0(s_{out} - s_0) + \frac{{V_{out}}^2}{2} + gz_{out} \quad (3.6)$$

This equation demonstrates one of the most important attributes of exergy: that the amount of useful work that can be extracted from a system is not measured by its enthalpic content, but rather that exergy is the maximum work that can be extracted by bringing the system to a state of equilibrium with the reference state [62].

Equation 3.5 can be formulated on a rate basis at steady state, allowing for exergy destruction rates of a steady state system, which are useful for optimizing a thermodynamic system, to be calculated:

$$\sum\left(\dot{X}_{Q_{in}} - \dot{X}_{Q_{out}}\right) + \sum\left(\dot{X}_{W_{in}} - \dot{X}_{W_{out}}\right) + \sum \dot{m}_{in}(\psi_{in} - \psi_{out}) - \dot{X}_{des} = \frac{dX_{sys}}{dt} = 0 \quad (3.7)$$

The exergy rate associated with heat transfer can be defined as follows, where T_b is the system boundary absolute temperature where heat is being transferred:

$$\dot{X}_Q = \dot{Q}\left(1 - \frac{T_o}{T_b}\right) \quad (3.8)$$

The exergy rate associated with work is defined as:

$$\dot{X}_W = \dot{W} \tag{3.9}$$

The exergy rate provided by the fuel input to the furnace can be approximated as the average higher heating value of the wood chip fuel multiplied by the mass flow rate:

$$\dot{X}_{fuel} = \dot{m}_{fuel} HHV_{fuel} \tag{3.10}$$

The exergy efficiency is defined in general terms as:

$$\eta_X = \frac{product\ exergy\ output}{exergy\ input} \tag{3.11}$$

This expression can be written for pumps and fans as:

$$\eta_X = \frac{\dot{m}_{in}(\psi_{out} - \psi_{in})}{\dot{W}_{in}} \tag{3.12}$$

For heat exchangers and heaters such as the boiler, the exergy efficiency can be written as the ratio of exergy transfer between the hot and cold fluids as follows, where $\dot{m}_{cold}$ and $\dot{m}_{hot}$ are defined as the mass flow rate of feed water and flue gases, respectively:

$$\eta_X = \frac{\dot{m}_{cold}(\psi_{out} - \psi_{in})_{cold}}{\dot{m}_{hot}(\psi_{out} - \psi_{in})_{hot}} \tag{3.13}$$

The exergy efficiency of the cycle can be written as:

$$\eta_X = \frac{\dot{X}_{campus} + \dot{X}_{chiller}}{\dot{X}_{fuel} + \sum \dot{X}_{pumps} + \sum \dot{X}_{fans}} \tag{3.14}$$

3.4 Case Study: University of Idaho Energy Plant

The district energy plant at UI provides over 120 million kg of steam to campus annually, with 95% of the load being supplied by the biomass boiler. The operating conditions of the biomass boiler at the time measurements were taken are listed in Table 3.1. Three backup natural gas boilers are used to supplement the biomass boiler during peak loads and during routine maintenance, but these are not considered in this analysis.

The primary purpose of the energy plant is to provide heating and cooling needs to campus throughout the year and as such does not produce electricity using a steam turbine. A turbine is not currently in use to minimize operating costs. Furthermore, a turbine sized to meet campus electricity demands would have reduced performance during the summer, when steam production is at a minimum. The result of this is that while the equipment configuration is similar to that of cogeneration plants, a dedicated condenser is not actually required in the plant and campus itself is able to reject enough heat to complete the thermodynamic cycle. Furthermore, steam pressure levels through the boiler are lower than those found in power plants to minimize pumping costs.

Table 3.1. Operating conditions of the biomass boiler.

Parameter	Value
Mass flow rate of fuel	0.54 kg/s
Average higher heating value of fuel [63]	13.6 MJ/kg
Moisture content of fuel by weight	36%
Ash content of fuel by weight	0.5%
O_2 level in flue gas	6.0%
Feed water inlet temperature	396.5 K
Steam flow rate	2.95 kg/s
Steam temperature	452 K
Steam pressure	977.3 kPa

The biomass fuel is comprised primarily of western red cedar from nearby lumber mills in the form of wood chips and slash. This is the waste material from lumber production, and would normally be transported to a landfill or burned. By weight, the wood chips have a higher heating value of 19.98-22.56 MJ/kg when measured on a dry basis [63]. The moisture content of the wood chips has a linear relationship with the average heating value:

$$Heating\ value = \frac{100\% - moisture\ content\ (\%)}{100\%} * HHV \qquad (3.15)$$

Using equation 3.15, the average higher heating value of the fuel, and thus its chemical exergy content, at the time of combustion can be determined when the moisture content is known. The biomass fueled boiler at UI provides the opportunity for the logging industry in the northwest to dispose of waste in an environmentally responsible manner, while at the same time allowing UI to produce steam sustainably at reduced costs and reduce dependence on fossil fuels.

A schematic diagram of the steam cycle through the biomass boiler is depicted in Figure 3.1. This system utilizes an economizer to preheat the feed water before it enters the boiler. The steam passes through a pressure reducing valve (PRV) before being conveyed to campus to reduce the pressure to levels more suitable for the needs in campus buildings. Approximately 3% of the steam is lost while on campus and required makeup water is introduced in the hot lime softener (HLS) tank. Introducing makeup water into the HLS allows for the water to be preheated before entering the de-aerator. Condensate from the absorption chiller and campus is returned at atmospheric pressure to the condensate tank. Three condensate pumps are located at the energy plant, however only one is in operation at any given moment.

An average of 0.5% of the wood chips by weight leaves the furnace as fly ash, which is removed from the flue gas in a multi-cone cyclonic separator. The heat in the flue gas leaving the boiler is recovered by the incoming combustion air in an air preheater. This reduces the flue gas temperature and thus exergy losses, and increases the efficiency of the cycle. Under-fire air introduced in the furnace is at ambient conditions.

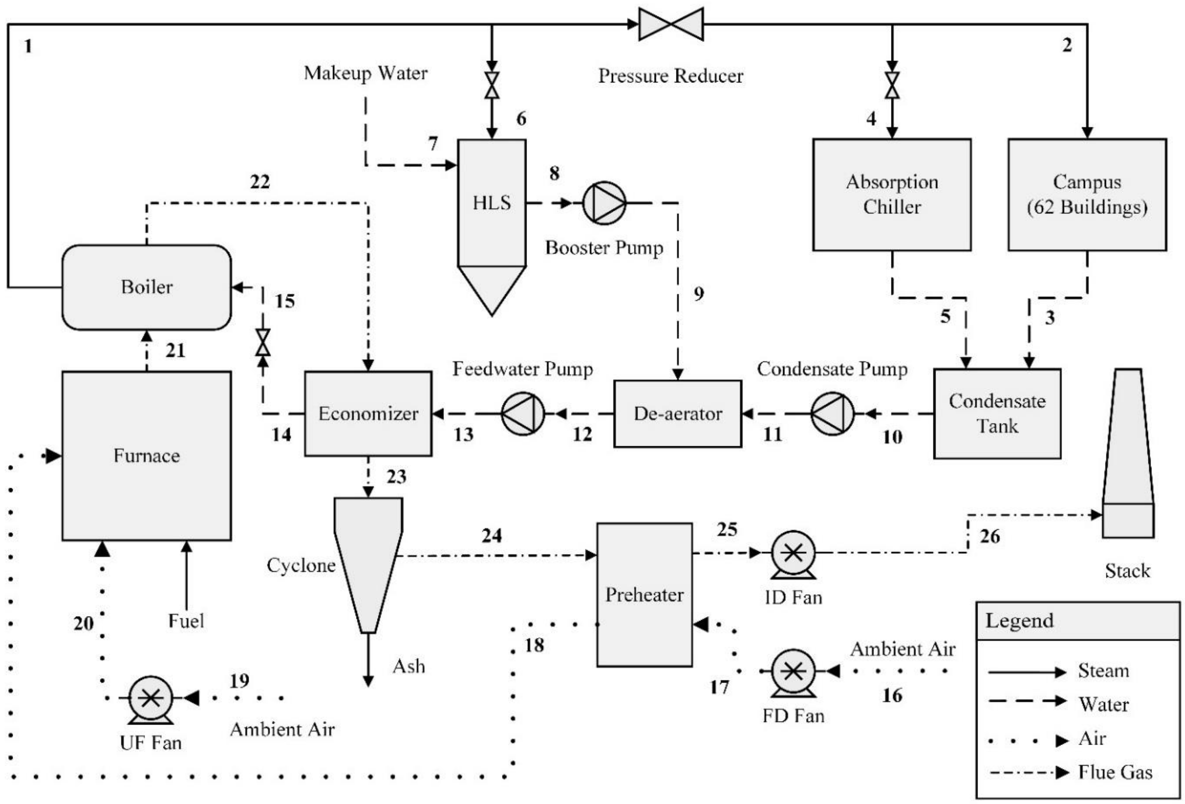

Figure 3.1. Flow diagram of the steam cycle including the biomass boiler.

3.5 Analysis

Using equation 3.6, the steam cycle was analyzed with a dead state set at a temperature of 300.4 K and a pressure of 101.7 kPa, which were the atmospheric conditions when time measurements were taken. Temperatures and pressures are monitored at each major component and the thermodynamic properties of each state point have been summarized in Table 3.2. These values fluctuate throughout the year as the seasons change, especially properties for ambient air, however most of the steam network is insulated. The exergy content of ambient air is very low compared to steam and the wood chip fuel, so its impact on this analysis is minimal. It should be noted however that energy and exergy efficiency calculations would be affected by ambient conditions. Additional air is added using computer controls as needed to maintain 2-6% excess oxygen levels in the exhaust. This ensures that a stoichiometric reaction occurs and all the wood fuel is consumed, eliminating the possibility of carbon monoxide (CO) and unburned hydrocarbons forming as well as raising energy efficiency.

Table 3.2. Data for flows and conditions of steam cycle when T_0=300.4 K, P_0=101.7 kPa.

Point	$\dot{m}$ (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg-K)	ψ (kJ/kg)
0	-	300.4	101.7	114.2	0.3982	-
1	2.949	452	977.3	2776	6.593	801.3
2	1.876	426.1	515.4	2749	6.811	709.2
3	1.819	373.2	101.7	419.5	1.308	31.99
4	0.9412	390.8	184.4	2703	7.154	559.1
5	0.9412	373.2	101.7	419.5	1.308	31.99
6	0.132	387.8	167.2	2698	7.187	544.8
7	0.05627	295.9	667.1	96.15	0.3358	0.7061
8	0.1882	385.4	223	470.8	1.443	42.71
9	0.1882	385.4	632.6	471.4	1.443	43.23
10	2.761	362.0	116.6	372.4	1.18	23.39
11	2.761	362.1	377.5	372.9	1.18	23.69
12	2.949	385.4	155.4	471.7	1.445	42.9
13	2.949	385.9	1625	474.2	1.448	44.67
14	2.949	396.5	1625	519	1.562	55.06
15	2.949	396.5	977.3	518.5	1.563	54.43
16	3.246	314.8	101.7	315.2	6.914	0.3389
17	3.246	315.3	102.1	315.7	6.914	0.7382
18	3.246	387	102.1	388.2	7.121	10.97
19	0.5127	300.4	101.7	300.7	6.867	-
20	0.5127	300.8	102.1	303.8	6.867	2.996
21	4.295	1829	101.7	2040	8.853	1143
22	4.295	486.5	101.7	489.5	7.356	41.98
23	4.295	456.5	101.7	458.8	7.291	30.84
24	4.292	456.5	101.4	458.8	7.291	30.63
25	4.292	402.7	101.4	404	7.164	14.19
26	4.292	403.2	101.7	404.5	7.164	14.54

Table 3.3 lists equations developed for each component in the system after applying equation 3.2 and equations 3.7-3.10. The ash content of the burned woodchips comprises <1.0% of the weight of the fuel and for the sake of this study is considered to have no exergy content. While neglected on an exergetic level, the ash is not disposed of, but instead is used by the agricultural department at UI to neutralize pH levels of soils. Since the installation of the biomass boiler in 1986 all the ash generated has remained on campus.

Table 3.3. Exergy destruction rate expressions and values for the system and its components.

Component	Equation	Exergy Destruction Rate (kW)
Absorption chiller	$\dot{X}_{des_{chiller}} = \dot{m}_4 * (\psi_4 - \psi_5) - \dot{Q}_{chiller}\left(1 - \frac{T_0}{T_5}\right)$	76.7
Boiler	$\dot{X}_{des_{boiler}} = \dot{m}_1 * (\psi_{15} - \psi_1) + \dot{m}_{21} * (\psi_{21} - \psi_{22})$	2528
Booster pump	$\dot{X}_{des_{booster}} = \dot{W}_{booster} + \dot{m}_8 * (\psi_8 - \psi_9)$	0.01
Campus	$\dot{X}_{des_{campus}} = \dot{m}_2 * \psi_2 - \dot{m}_3 * \psi_3 - \dot{Q}_{campus}\left(1 - \frac{T_0}{T_3}\right)$	414
Condensate pump	$\dot{X}_{des_{cond}} = \dot{W}_{cond} + \dot{m}_{10} * (\psi_{10} - \psi_{11})$	0.41
Condensate tank	$\dot{X}_{des_{CT}} = \dot{m}_3 * \psi_3 + \dot{m}_5 * \psi_5 - \dot{m}_{10} * \psi_{10}$	23.7
Cyclone	$\dot{X}_{des_{cyclone}} = \dot{m}_{23} * \psi_{23} - \dot{m}_{24} * \psi_{24}$	0.99
De-aerator	$\dot{X}_{des_{DA}} = \dot{m}_9 * \psi_9 + \dot{m}_{11} * \psi_{11} - \dot{m}_{12} * \psi_{12} + \dot{Q}_{HLS}\left(1 - \frac{T_0}{T_{12}}\right)$	7.21
Economizer	$\dot{X}_{des_{econ}} = \dot{m}_{13} * (\psi_{13} - \psi_{14}) + \dot{m}_{20} * (\psi_{22} - \psi_{23})$	17.2
Exhaust	-	62.4
FD fan	$\dot{X}_{des_{FD}} = \dot{W}_{FD} + \dot{m}_{16} * (\psi_{16} - \psi_{17})$	0.12
Feed water pump	$\dot{X}_{des_{feed}} = \dot{W}_{feed} + \dot{m}_{12} * (\psi_{12} - \psi_{13})$	2.4
Furnace	$\dot{X}_{des_{furnace}} = \dot{X}_{fuel} + \dot{m}_{18} * \psi_{18} + \dot{m}_{20} * \psi_{20} - \dot{m}_{21} * \psi_{21}$	2428
HLS tank	$\dot{X}_{des_{HLS}} = \dot{m}_6 * \psi_6 + \dot{m}_7 * \psi_7 - \dot{m}_8 * \psi_8 - \dot{Q}_{HLS}\left(1 - \frac{T_0}{T_8}\right)$	3.71
ID fan	$\dot{X}_{des_{ID}} = \dot{W}_{ID} + \dot{m}_{25} * (\psi_{25} - \psi_{26})$	0.45
Preheater	$\dot{X}_{des_{PH}} = \dot{m}_{17} * (\psi_{17} - \psi_{18}) + \dot{m}_{24} * (\psi_{24} - \psi_{25})$	37.9
PRV	$\dot{X}_{des_{PR}} = (\dot{m}_1 - \dot{m}_6) * \psi_1 - (\dot{m}_2 + \dot{m}_4) * \psi_2$	260
UF fan	$\dot{X}_{des_{UF}} = \dot{W}_{UF} + \dot{m}_{19} * (\psi_{19} - \psi_{20})$	0.05
Total		5863

3.6 Results and Discussion

Exergy destruction rates are summarized in Table 3.3 for each component in the steam cycle. The largest sources of exergy destruction are the boiler and furnace with 2528 kW and 2428 kW, respectively. Figure 3.2 illustrates the exergy flow rates into and out of the boiler system; values are obtained by multiplying the mass flow rate by the specific flow exergy. Exergy in the flue gas is recovered in an economizer and air preheater before reaching the stack. While not a direct result of exergy destruction through a component, it should be noted that 62 kW of the exergy rate of the combustion products is exhausted to the atmosphere. More exergy can be recovered as the flue gas temperature is brought closer to the ambient temperature, however if temperatures are lowered too much the combustion products will begin to condense in the stack, accelerating corrosion.

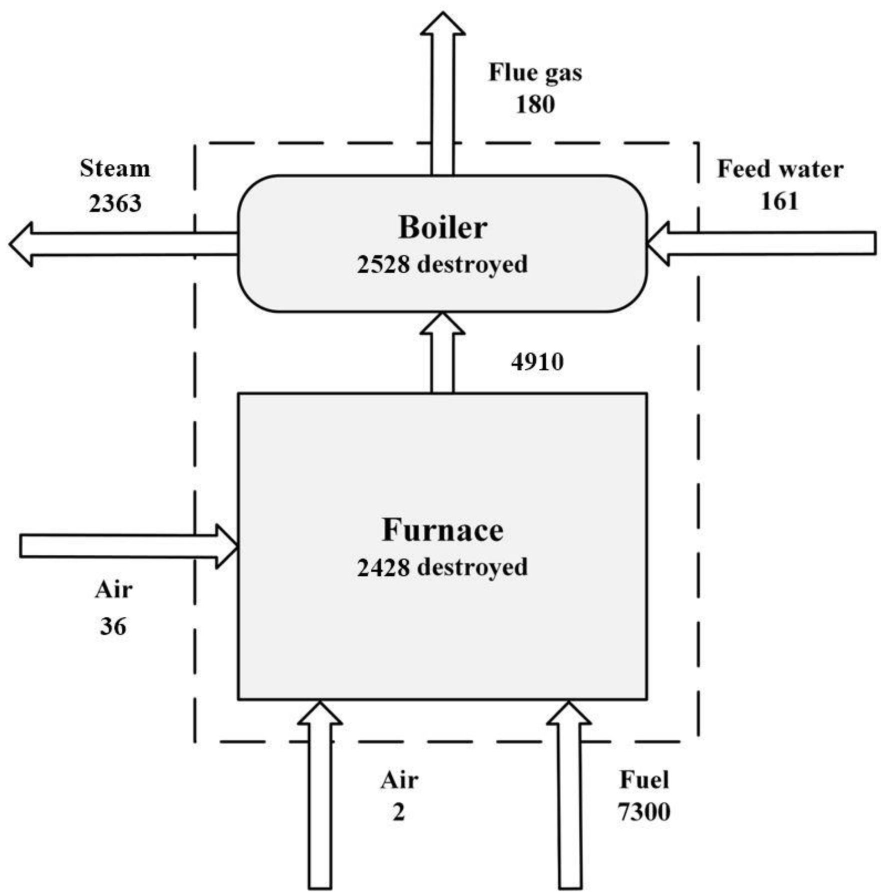

Figure 3.2. Exergy flow and destruction rates (in kW) for the biomass boiler and furnace.

3.6.1 Impact Assessment

With equations 3.4 and 3.14, the cycle energy and exergy efficiencies are found to be 90% and 17%, respectively. This low exergy efficiency, especially compared to the energy efficiency, indicates that opportunities for improvement can in theory be found, but of course these are subject to physical, economic, and other constraints. The percentage of exergy destroyed relative to the exergy input for each component can be expressed as follows:

$$\dot{X}_d(\%) = \frac{\dot{X}_d}{exergy\ input} * 100(\%) \tag{3.16}$$

The results of applying this equation to each component are shown in Figure 3.3. The boiler and furnace account for the majority of the exergy losses in the system. This is in part due to the nature of the combustion and heat transfer processes as well as the relatively low heating value of the biomass fuel compared to fossil fuels. With a measured moisture content of 36% in the fuel, increased fuel feed rates are required to produce the required amount of steam which in turn destroys more exergy for the same result. Note however that while larger flow rates of fuel are required for the combustion of biomass, this fuel source results in substantial economic savings compared to natural gas, is sustainable on a long-term scale, and emits no net CO_2 to the environment.

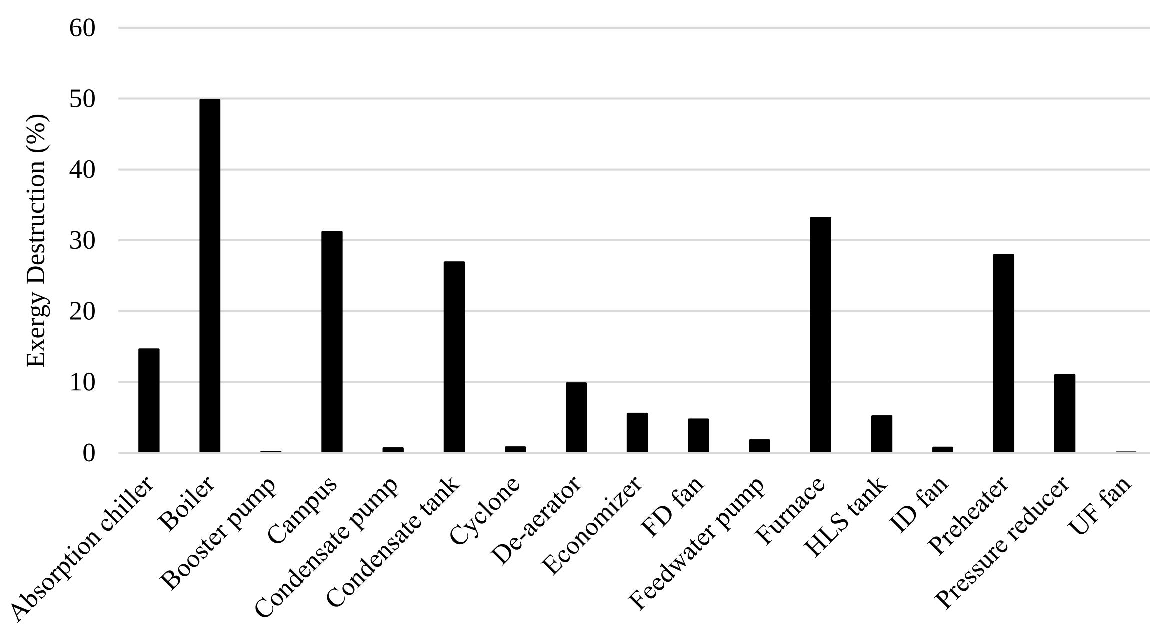

Figure 3.3. Percentage of incoming exergy destroyed in each component.

The expression in equation 3.16 can be modified as follows to show the relation of exergy destroyed in each component with that of the primary source of exergy supplied to the cycle:

$$\dot{X}_{d_{fuel}}(\%) = \frac{\dot{X}_d}{\dot{X}_{fuel}} * 100(\%) \tag{3.17}$$

Figure 3.4 demonstrates the importance of using a common reference point, provided by equation 3.17, when investigating sources of exergy destruction. Many components in the cycle destroy significant amounts of the flow exergy, indicating that improvements could be made. However, these flow exergies are often very small compared to the exergy input from the fuel. Equation 3.17 shows that the largest sources of exergy destruction compared to the fuel input are found in the boiler and furnace at approximately 35% and 33% of losses, respectively, followed by the heating equipment used on campus at 5.7% and the PRV at 3.5%. The boiler/furnace performance results are similar to those found by Sengupta, et al. when investigating exergy destruction rates in a coal fired power plant [64]. They saw an approximate exergy destruction rate of 60% in the boiler system, compared to 68% at the UI. Improvement and optimization efforts for the system are often more rational if they start at the components with the largest opportunities for improvement, to improve or maximize the potential benefits.

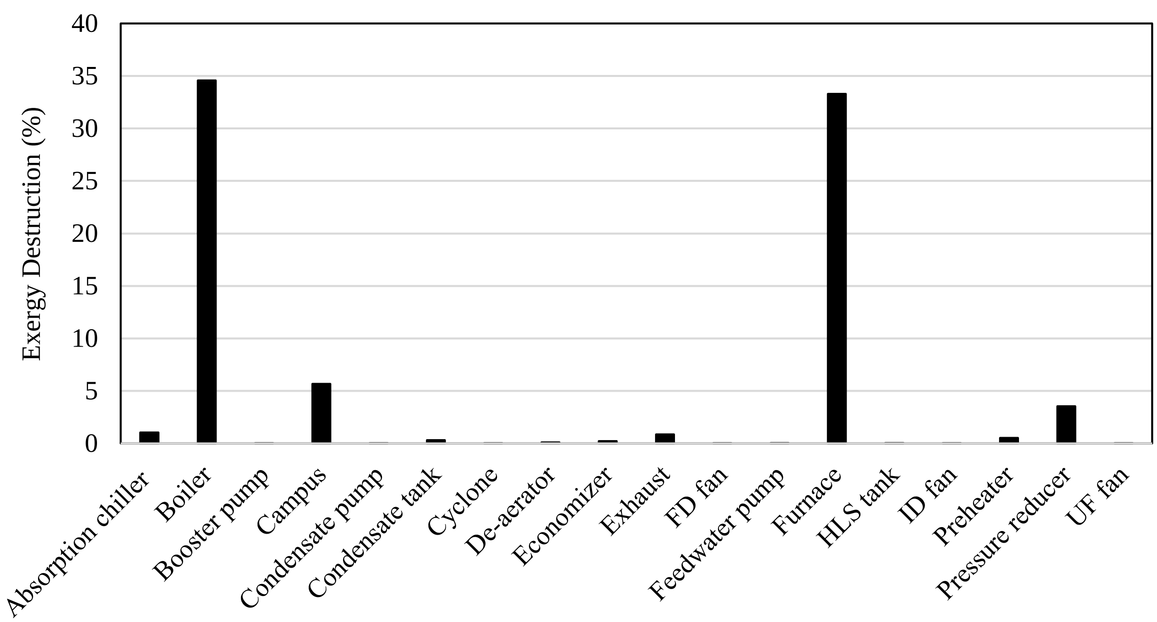

Figure 3.4. Percentage of exergy destroyed in each component relative to exergy input with fuel.

3.6.2 Improvement Assessment

With the primary sources of exergy destruction in the steam cycle known, methods of increasing the exergy efficiency are investigated. A parametric study of the steam pressure in the boiler is carried out to determine how varying pressure levels affects the exergy efficiencies and destruction rates of the boiler and the PRV. In the analysis, pressure is adjusted from the same level as after the PRV, essentially eliminating the component, up to twice the current level. The results (see Figure 3.5) show that the exergy destruction rates increase through the PRV with increased steam pressure. Exergy destruction rates through the boiler decrease with higher steam pressure levels, however, indicating that the boiler benefits thermodynamically from increased pressure levels.

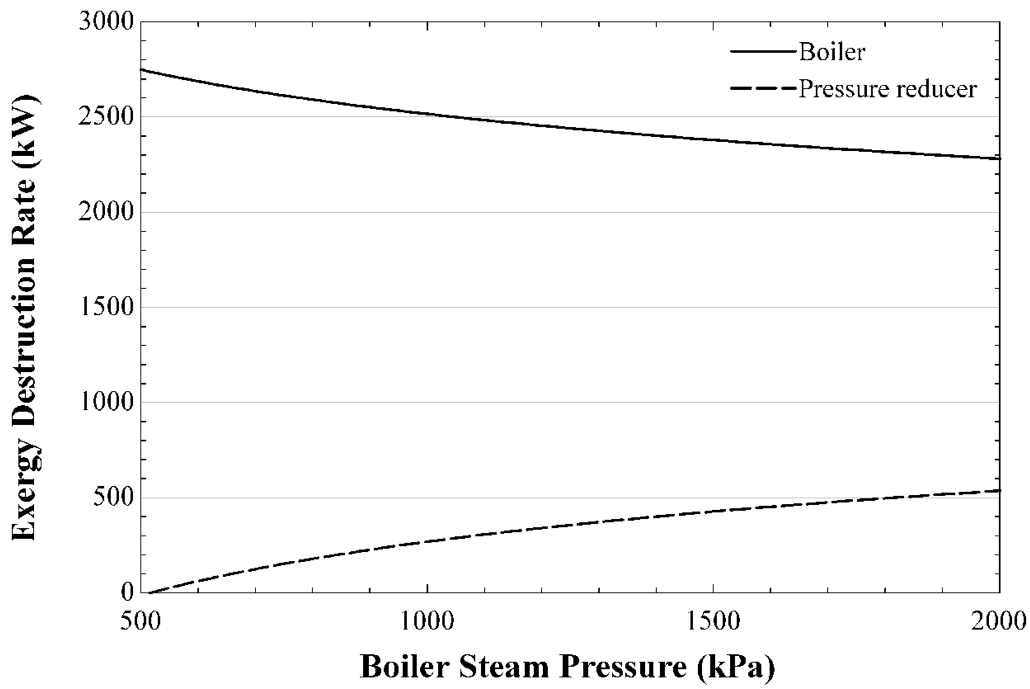

Figure 3.5. Exergy destruction rate vs steam pressure level through the boiler.

The biomass boiler and pipe network is capable of supplying steam at pressure levels of 4000 kPa, however the natural gas backup boilers are rated for 1400 kPa. Broadening the scope of adjusting boiler steam pressure levels, the effect on the boiler and overall cycle exergy efficiency is shown in Figure 3.6. It can be seen that the total cycle efficiency decreases marginally as the pressure level in the boiler increases. Regulagadda et al. showed that cycle energy and exergy efficiency should improve with increasing steam pressure through the boiler in an exergy accounting of a coal fired power plant [5]. By producing electricity with a turbine and generator, they do not need to use a PRV to control steam pressure levels. This indicates that the PRV is limiting potential improvements made in the boiler at UI. One possible solution to this problem would be to replace the component entirely with a turbine to produce electricity while bringing the pressure down for use on campus. As work is defined in equation 3.9 as pure exergy, this would result in a substantial increase in exergy efficiency.

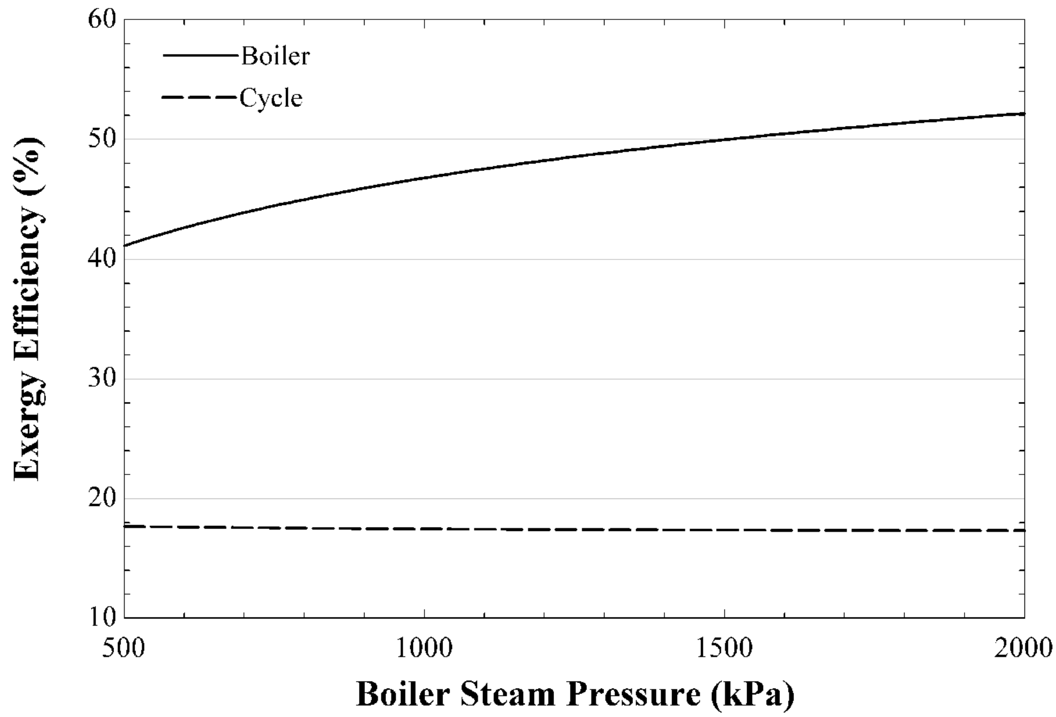

Figure 3.6. Exergy efficiency of boiler and cycle vs steam pressure in the boiler.

Increasing the exergy efficiency of the boiler by reducing the required fuel input is also investigated. Fuel requirements can be reduced by minimizing the moisture content of the fuel before combustion. By increasing the HHV of the fuel, efficiency of the system will improve. Reductions in fuel input would also result in reduced emissions to the environment and increased exergy efficiency of the entire system. Equation 3.15 shows the negative correlation between the higher heating values of biomass and its moisture content, as shown in Figure 3.7. This relation is due to some of the combustion heat being used to evaporate the moisture content in the fuel. At UI, the moisture content of the wood chips received ranges from 6% by weight to nearly 60% during adverse weather conditions, with a yearly average of 30%. Since the moisture content in biomass has a direct impact on the higher heating value and thus the mass flow rate of fuel, steps are taken to reduce the moisture content before combustion. A covered storage facility located on campus uses natural convection from wind currents to reduce the moisture content approximately 10% before the biomass is sent to the energy plant. This increases the efficiency of the combustion process.

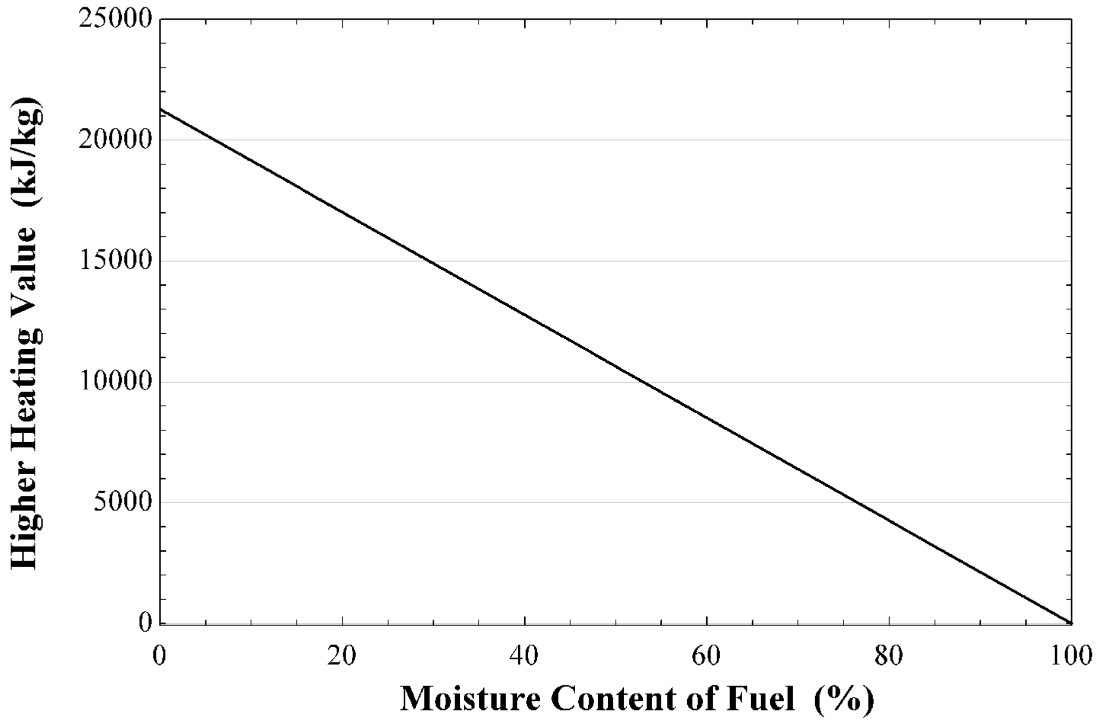

Figure 3.7. Average higher heating value of fuel vs moisture content.

3.7 Conclusions

The study demonstrates which components in the steam cycle would benefit from enhancement and/or optimization. Exergy destruction rates in the energy plant are as follows:

- 35% in the boiler
- 33% in the furnace
- 6% from campus heating equipment and steam distribution network
- 3.5% in the pressure reducing valve

The high exergy destruction rate in the furnace is due to the nature of the combustion and heat transfer processes and the low exergy content of the fuel relative to fossil fuels. Possible methods of reducing exergy losses in these components include improvements in the heating equipment on campus as well as modifying the current plant by installing a steam turbine and generator to create a cogeneration cycle for electricity production. A small single stage turbine able to offset some operating costs would operate at a higher efficiency than a larger turbine capable of supplying all of the electricity demands on campus. Both measures merit future investigations using economic analyses as potential ways to improve the cycle.

Steam pressure through the boiler is kept low to reduce pumping costs since there is not a need for higher pressure levels. It is shown however that increasing the boiler pressure increases exergy efficiency. Coupled with a turbine to improve the full cycle, increased pumping costs would likely be offset by the improved efficiency and power generation. This highlights the importance of investigating the relationships between components in a system and is applicable to both current and future systems.

The nearly exclusive use of biomass fuel allows for UI to have a long term sustainable fuel source; however, improvements are possible in efficiency. Moisture content has a direct impact on the amount of fuel required and as such efforts may be worth undertaking to lower or minimize it. Biomass does not emit net CO_2 to the atmosphere during the combustion process since the CO_2 was originally absorbed by the biomass during its life cycle. Proximity to a suitable fuel source can play a major role in its use however, as the economic and environmental costs of transporting fuel to the plant may not be feasible compared to those for fuels such as natural gas.

Expanding the scope of this assessment to the natural gas boilers would provide further insight into the sustainability of the energy plant and provide a comparison of biomass against fossil fuels in a similar environment. Each boiler in the energy plant has different equipment configurations and an exergy analysis of each cycle would show the thermodynamic impacts of major components such as economizers and preheaters versus boilers without such equipment. Furthermore, an analysis of the district heating network through campus, including piping and building usage, could identify where additional improvements can be made.

Chapter 4: Investigating Steam Turbine Feasibility to Improve the Sustainability of a Biomass Boiler Using TRNSYS

Forthcoming in *Sustainable Cities and Society*

4.1 Abstract

Adding a turbine to a steam generator plant of a district energy system increases the efficiency of the plant by generating some electricity. This is the method of turning a heating and cooling plant into a combined heating, cooling, and power (CHCP) plant. The district energy plant at University of Idaho, Moscow, Idaho, USA is modeled by using TRNSYS modeling software. Simulation of different models is made for a comparison between the current system configuration (heating and cooling), the heating and cooling plus a small backpressure steam turbine, and adding a double effect absorption chiller. Operating costs, energy, and exergy efficiency are evaluated at current and maximum steam pressure levels through the boiler and turbine. Primary components in the system include a wood chip fired boiler, steam turbine, 2100 kW (600 RT) single effect and 4100 kW (1200 ton) double effect absorption chillers, and campus with associated pumping needs. It is found that installing a turbine and increasing pressure to maximum possible levels would improve energy and exergy efficiency by 3-4% and 5%, respectively over current levels. Bringing a double effect chiller in addition to the turbine increases energy and exergy efficiencies further to 20% and 7%. Economic savings are substantial if power can be sold back to the utility at a higher rate.

4.2 Introduction

Modern society's demand for more energy has been one of its biggest challenges, a trend that has shown no signs of stopping. In recent centuries, this demand has been satisfied by extracting fossil fuel resources such as coal, oil, and natural gas. These resources cannot be replenished on a time scale that is sustainable and will eventually run out. Renewable energy resources have the potential to replace fossil fuels as the dominant source of energy. However, while extensive work has been done to harness solar, wind, biomass, and many other energy sources, the technology is not yet at a point where it can reliably replace our dependence on fossil fuels. It is for this reason that we must utilize the energy resources available, no matter their origin, as efficiently as possible.

One of the ways energy resources can be used efficiently is in district energy (DE) applications. DE systems can produce heating, cooling, and electricity in a central location, where it is then distributed for use in buildings. By uses a central plant, less efficient equipment is eliminated from the individual buildings. These systems have been shown to meet energy demands with reduced greenhouse gas emissions compared to more traditional systems [11]. DE systems using non fossil fuels have also been shown to be economically advantageous compared to fossil fuels after considering taxes associated with CO_2 emissions [14].

The energy plant at the University of Idaho (UI) has been operating for over ninety years, with many expansions and upgrades throughout its life. Originally using coal as the primary fuel source, UI eventually switched to natural gas and today uses biomass in the form of wood chips, resulting in significant economic savings without relying on fossil fuels [52]. Recently, to increase the cooling capacity a 7500 m^3 cold thermal energy storage (TES) tank was added to the UI district heating and cooling in the Moscow, ID campus. The UI energy plant has capacity for more advancement by integrating a turbine for generating electricity. Combined heat and power (CHP) plants, also known as cogeneration plants, have been in use for decades. During warm summer periods, traditional CHP plants have difficulty discharging sufficient heat. This limits the amount of power than can be produced and presents an opportunity to utilize waste heat to produce cooling in what is referred to as combined heating, cooling, and power (CHCP), or trigeneration. Szega and Żymelka presented a thermo-economic analysis of producing cold through the use of single effect absorption chillers in a trigeneration plant [65]. They concluded that producing cold allowed for increased electricity production at the cost of increased fuel consumption. There has been research using TRNSYS modeling software to determine the feasibility of integrating cooling into a CHP system. Pagliarini et al. performed an economic analysis and determined that there is a point where the operating costs of a CHCP system outweigh the selling cost of electricity, i.e. it eventually becomes cheaper to buy power than produce it [66]. Drake also investigated improvements in a university campus using TRNSYS [67]. He discovered that the economic costs of additional piping to expand the system were not feasible, however upgrading the current steam network did result in reduced annual operating costs. Lake, et al. have investigated the reduction in greenhouse gases when CHP technology is integrated with CHCP [13]. The potential for CHCP to reduce environmental impacts through the reduction of greenhouse gases has been shown by Schicktanz et al. as well[68].

Exergy is defined as the maximum amount of work that can be extracted from a process in a reference environment [24]. Exergy accounting allows for the inputs, losses, and wastes of a process to be identified since exergy is not a conserved quantity like mass and energy [22]. Sciubba and Wall have reviewed the development of exergy in recent years [43]. Szargut et al. have suggested that taking an exergy approach to increase system efficiency can reduce the system's impact on the environment [42]. Connections between energy, exergy, and long term sustainability have been identified by Dincer and Rosen as well [3], [46], [69].

Efforts have been made to improve the energy and exergy efficiency of thermal power plants and district energy systems using TRNSYS software. Kallert et al. have demonstrated potential benefits when using an exergy approach to improve performance in low-temperature district heating networks [70]. Adibhatla and Kaushik investigated the energy efficiency, exergy efficiency, fuel savings, and solar contribution of a conceptual improvement to a 500 MWe coal fired power plant with TES [71]. They showed that a solar aided feed water heating network could improve system performance with a low payback period. Alam et al. investigated the feasibility of using solar thermal energy to preheat feed water [72]. They developed a method for determining the economic impacts of integrating solar thermal energy with conventional power plants.

The focus of this study is to improve the performance of the current cycle while minimizing capital investment. Boilers consume significant amounts of energy in any system and they must be used in the most efficient manner possible to realize economic and environmental benefits. The impact of installing a small single stage, backpressure steam turbine to replace the pressure reducing valve (PRV) as the primary means of reducing steam pressure in the system as a solution is investigated. The impact on system performance with the installation of a double effect absorption chiller is also investigated. Furthermore, energy and exergy efficiency is calculated, as well as the operating costs of the system during the peak heating and cooling months for each configuration.

4.3 Methodology

4.3.1 Exergy Analysis

An exergy analysis allows for the environmental impact of a process to be determined. There is a fundamental difference between energy and exergy. In an energy balance, both heat and work have the same value, however work has a higher exergy value than heat and therefore the use of an exergy analysis can be more appropriate when investigating impacts on the environment [73]. The exergy rate associated with heat transfer is written as follows, where T_b is the system boundary temperature where heat is being transferred

$$\dot{X}_Q = \dot{Q}\left(1 - \frac{T_o}{T_b}\right) \quad (4.1)$$

This can be applied to both the campus and absorption chiller components in the model. The exergy rate associated with work is defined as

$$\dot{X}_W = \dot{W} \quad (4.2)$$

The exergy rate from the fuel input to the boiler can be approximated as the following, where HHV is the average higher heating value of the wood chips and has a value of 20.6 MJ/kg [63]

$$\dot{X}_{fuel} = \dot{m}_{fuel} HHV_{fuel} \quad (4.3)$$

The energy efficiency of the cycle considered here, which is a measure of how much useful energy is produced from a given input, is expressed as follows

$$\eta_{energy} = \frac{product\ energy\ output}{energy\ input} \quad (4.4)$$

Which can be written as the following for the system

$$\eta_{energy} = \frac{\dot{Q}_{campus} + \sum \dot{Q}_{chillers} + \dot{W}_{turbine}}{\dot{X}_{fuel} + \sum \dot{W}_{pumps}} \quad (4.5)$$

The exergy efficiency is defined in general terms as

$$\eta_X = \frac{product\ exergy\ output}{exergy\ input} \tag{4.6}$$

Which is written as the following for the system as

$$\eta_X = \frac{\dot{X}_{campus} + \sum \dot{X}_{chillers} + \dot{X}_{turbine}}{\dot{X}_{fuel} + \sum \dot{X}_{pumps}} \tag{4.7}$$

4.3.2 Transient System Simulation Tool (TRNSYS)

The energy plant at the UI main campus is modeled using the TRNSYS software tool. TRNSYS was selected for its extensive component library and modeling capabilities, particularly in renewable energy sources and electric power generation [74]. Figure 4.1 shows the graphical representation of the energy plant in the TRNSYS interface. The top center area shows the steam turbine, PRV, and double effect absorption chiller in a parallel configuration. The campus heating load and single effect absorption chiller is on the right side of the diagram, also in parallel. The lower left contains the boiler, deaerator, and pumps. Type 618 is designated as the feed water pump and Type 618-2 is the condensate pump. The simulation is run for one month.

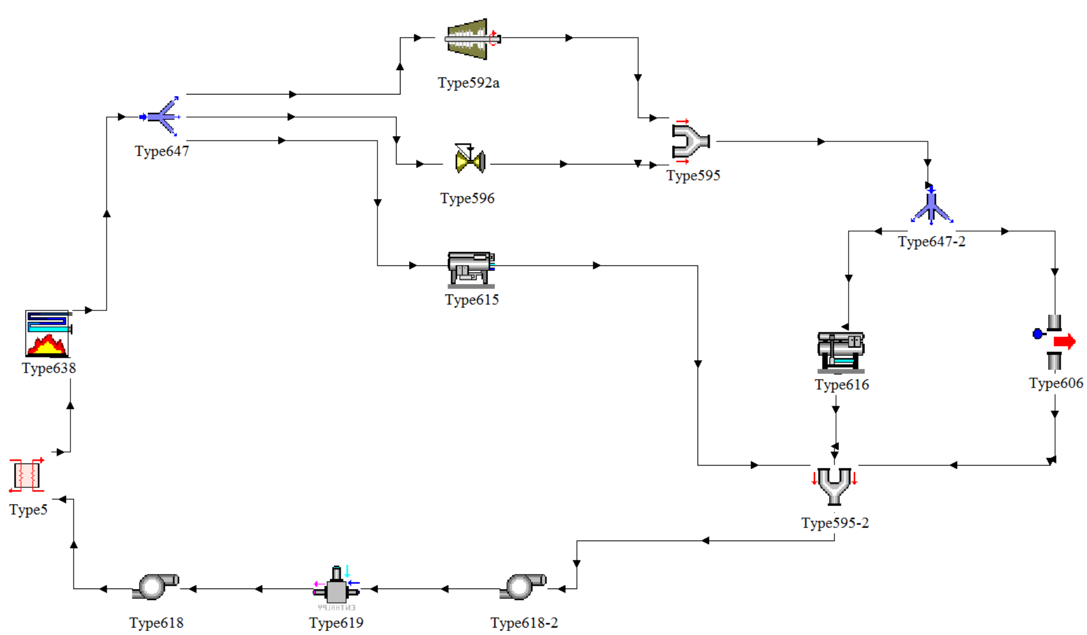

Figure 4.1. Graphical representation of the UI energy plant in TRNSYS including steam turbine and double effect absorption chiller.

Table 4.1 outlines the TRNSYS components, known as “types,” that are selected to model the energy plant as well as the required inputs for each component. Input values are based on measurements taken or manufacturer’s equipment specifications. The required steam production and pressure is provided as an input to the feed water pump in the form of condensate, which sets the mass flow through the boiler. The boiler efficiency is defined as the boiler’s overall ability to produce steam and it is used to calculate the fuel input energy required. The combustion efficiency accounts for losses such as energy leaving in the flue gases and radiative losses through the exposed surfaces of the boiler to the environment.

Some assumptions must be made for this model. The absorption chillers are assumed to be always running at capacity throughout the simulation, which reflects typical operating conditions during the summer months. With cold storage capacity on campus available, any excess chilled water produced can be stored for use later. The campus load is assumed to be able to reject all of the incoming heat energy and return condensate back to the energy plant. This is important, as the summer heating requirements are very low compared to the winter steam load and thus the amount of steam needed is reduced. Losses through the piping network have been neglected and a constant 3% makeup water requirement is assumed, which is introduced in the deaerator component. Makeup water requirements are generally stable through the year and are based on annual averages for the plant. All pumps are assumed to have an energy efficiency of 60%.

The installation of a double effect absorption chiller requires an increase in steam production to continue meeting the campus heating load needs. This is because once the steam has been used by the double effect chiller, the steam condensate must be returned to the condensate tank in the energy plant instead of continuing to either the single effect chiller or campus. The double effect chiller requires a high-pressure steam source and must be run in parallel with the turbine and PRV, whereas the single effect chiller can utilize low-pressure steam. This results in a lost opportunity to produce power, as the steam cannot pass through both the turbine and the double effect chiller.

Table 4.1. Description of system components in TRNSYS with required inputs [74].

Boiler:	Type 638 models a steam boiler with capacity constraints by attempting to meet the user-specified steam outlet condition. Using efficiency as an input, fuel consumption can be calculated based on the required steam input energy.	
	Rated Capacity (kW)	17057
	Steam inlet temperature (°C)	123
	Steam inlet enthalpy (kJ/kg)	519
	Boiler efficiency	76%
	Combustion efficiency	85%
	Desired outlet enthalpy (kJ/kg)	3103
Steam turbine:	Type 592a models a non-condensing steam turbine that takes a user-specified inlet steam flow and calculates the total electrical load the turbine can meet. The model uses an isentropic efficiency approach, together with the desired steam backpressure, to determine turbine performance.	
	Capacity (kW)	1500
	Isentropic efficiency	85%
	Steam exhaust pressure (kPa)	515
PRV:	Type 596 models a steam pressure-reducing valve where steam adiabatically expands to the desired outlet pressure.	
	Desired outlet pressure (kPa)	515
Double effect absorber:	Type 615 models a double effect steam-fired absorption chiller using manufacturer's performance data files. The component will attempt to deliver the user-specified set point temperature for the chilled water stream based on the current cooling capacity.	
	Design capacity (kW)	4097
	Design C.O.P.	1.21
	Auxiliary electrical power (kW)	22.4
	Chilled water inlet temperature (°C)	12.2
	Chilled water flowrate (kg/s)	146.3
	Chilled water set point (°C)	6.7
	Cooling water inlet temperature (°C)	29.4
	Cooling water flowrate (kg/s)	260
Single effect absorber:	Type 616 models a single effect steam-fired absorption chiller using manufacturer's performance data files. The component will attempt to deliver the user-specified set point temperature for the chilled water stream based on the current cooling capacity.	
	Design capacity (kW)	2170
	Design C.O.P.	0.8
	Auxiliary electrical power (kW)	5.0
	Chilled water inlet temperature (°C)	12.2
	Chilled water flowrate (kg/s)	93.4
	Chilled water set point (°C)	6.67
	Cooling water inlet temperature (°C)	29.4
	Cooling water flowrate (kg/s)	163.5

Campus:	Type 606 models a simple end-use steam device. The user specifies inlet and outlet conditions along with the fraction of steam returned in the form of condensate. The component is useful for modeling complicated devices such as the steam heating and distribution network for buildings without needing to model the heat transfer physics.	
	Outlet steam pressure (kPa)	101.3
	Outlet steam enthalpy (kJ/kg)	420
	Fraction of steam returned	0.97
Condensate pump:	Type 618 models a steam condensate pump. Using user-specified inlet steam condensate conditions and the desired outlet pressure the model calculates the theoretical power from a compressed liquid calculation. Actual power is then calculated by dividing theoretical power by efficiency.	
	Overall pump efficiency	60%
	Pump motor efficiency	90%
	Desired outlet pressure (kPa)	378
Deaerator:	Type 619 models an open steam heater in which high temperature source steam at a variable flow rate is mixed with low temperature steam at a known flow rate to elevate the low temperature steam to a user-specified outlet condition.	
	Source steam temperature (°C)	114
	Source steam pressure (kPa)	167
	Source steam enthalpy (kJ/kg)	2698
	Desired outlet enthalpy (kJ/kg)	472
Feed water pump:	Type 618 models a steam condensate pump. Using user-specified inlet steam condensate conditions and the desired outlet pressure the model calculates the theoretical power from a compressed liquid calculation. Actual power is then calculated by dividing theoretical power by efficiency.	
	Overall pump efficiency	60%
	Pump motor efficiency	90%
	Desired outlet pressure (kPa)	1481
Counter flow economizer:	Type 5 models a zero-capacitance heat exchanger without mixing. The effectiveness is calculated given the hot and cold side inlet temperatures and flow rates. The source side is defined as the steam condensate coming from the feed water pump. The load side is defined as the exhaust gases from the boiler which are used to preheat the feed water.	
	Specific heat of source side fluid (kJ/kg-K)	1.026
	Specific heat of load side fluid (kJ/kg-K)	1.901
	Load side inlet temperature (°C)	213
	Load side flow rate (kg/s)	4.3

4.4 Case Studies

UI is in an interesting position, since producing cooling is not as widespread as power generation. There has been little research in literature for upgrading a system with heating and cooling already by generating power. More advanced turbine configurations can be implemented and have been explored at UI previously. Examples range from single stage turbines to configurations with larger, multistage steam turbines utilizing reheat stages producing steam at constant flow rates throughout the entire year. These studies have only investigated the initial capital costs and rate of return without addressing the environmental impact through an exergy analysis or the impacts on chilled water production via absorption chillers.

Operating costs can vary widely due to a variety of factors including location, fuel choice, and the negotiated electricity rates from utility companies. At the time of this study, UI purchased wood fuel at an average of $56.22 per bone dry metric ton (BDMT) ($51 per bone dry imperial ton (BDT)) and electricity from the utility is purchased at $0.059 per kWh. Electricity generated from renewable energy sources, such as biomass, can be sold back to the utility at $0.12 per kWh. This rate is based on previous negotiations with the utility. For the purpose of this study it assumed that all of the electricity generated by the turbine/generator is sold back to the utility company at the higher rate instead of consumed locally.

Figure 4.2 shows the existing energy plant configuration. Primary components include the 18.3 MW biomass fed boiler, 2100 kW single effect absorption chiller, economizer, and air preheater. This cycle is modified to place the steam turbine in parallel with the PRV, as shown previously in Figure 4.1. To analyze the UI energy plant, separate models are developed for July and December, using steam production data during the corresponding months in 2015, to represent the peak cooling and heating requirements of the Moscow campus. The mass flow rate of steam through the turbine can fluctuate to match actual steam production rates instead of attempting to meet a constant load throughout the simulation.

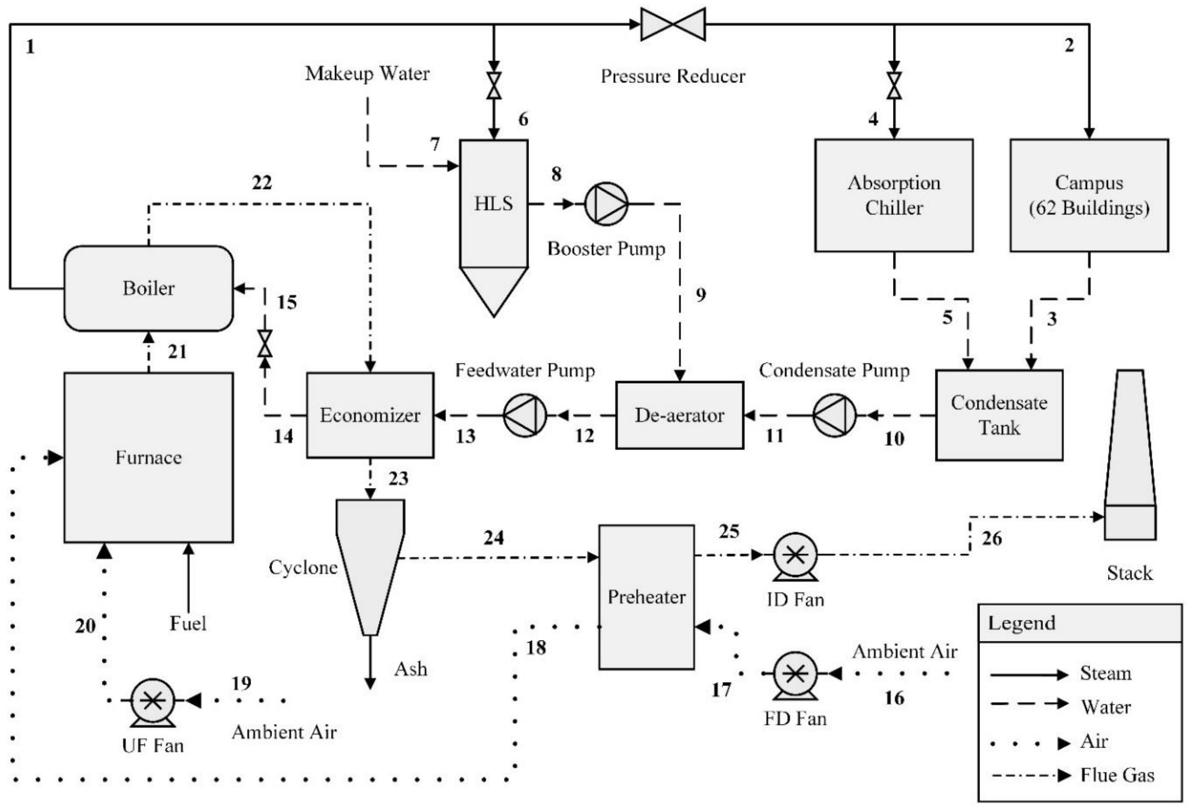

Figure 4.2. Flow diagram of the current UI steam cycle including the biomass boiler and single effect absorption chiller.

The key features of each case study are presented in the following sections and summarized below in Table 4.2. Details include which month of the year is being modeled, the pressure ratio across the turbine and/or PRV, whether the turbine is present in the case study, and which, if any, absorption chillers are in operation. Currently, the biomass boiler produces steam at 977 kPa. Some case studies investigate increasing this pressure to 1481 kPa, which is the operating pressure of the natural gas backup boilers. This is the maximum steam pressure that can be maintained at the energy plant without modification.

4.4.1 Baseline July model

The energy plant is modeled using the actual configuration and steam production data in July. This provides a baseline for fuel consumption, energy efficiency, and exergy efficiency of the plant in the summer. No turbine is present in this model and all the steam produced passes through the PRV. Steam is produced in the boiler at a pressure of 977 kPa and drops to 515 kPa after the PRV. A 2100 kW single effect absorption chiller is operating at a steady rate in parallel with the campus steam load.

4.4.2 Case study 1 – July model with turbine

A load following steam turbine is modeled using July steam production data. Inlet steam pressure is 977 kPa and steam exhaust pressure is 515 kPa. All the steam produced by the boiler is passed through the turbine, at the conditions shown in Table 4.1, instead of the PRV. A 2100 kW single effect absorption chiller is operating at a steady rate in parallel with the campus steam load.

4.4.3 Case study 2 – July model with turbine at increased pressure

The load following steam turbine is modeled using July steam production data. Inlet steam pressure is increased to 1481 kPa and steam exhaust pressure is 515 kPa. This larger pressure drop across the turbine will produce more power than the previous case study. All the steam produced by the boiler is passed through the turbine at the conditions shown in Table 4.1. The single effect absorption chiller is operating at a steady rate in parallel with the campus steam load.

4.4.4 Case study 3 – July model with turbine and double effect absorption chiller

The load following steam turbine is modeled using July steam production data. Inlet steam pressure is 977 kPa and steam exhaust pressure is 515 kPa. A 4100 kW double effect absorption chiller is modeled in a parallel configuration with the steam turbine and PRV. Steam produced by the boiler passes through both components. The double effect absorption chiller draws enough steam to meet load requirements when running at capacity. Condensate leaving the double effect chiller enters the condensate tank in the plant to be reused later. The remaining steam passes through the turbine. The single effect absorption chiller is operating at capacity in parallel with the campus steam load.

4.4.5 Case study 4 – July model with turbine, double effect absorption chiller, and increased pressure

The load following steam turbine is modeled using July steam production data. Inlet steam pressure is increased to 1481 kPa and steam exhaust pressure is 515 kPa. The 4100 kW double effect absorption chiller is modeled in parallel with the steam turbine and PRV. Steam produced by the boiler passes through both components. The double effect absorption chiller draws enough steam to meet the load requirements when running at capacity. Condensate leaving the double effect chiller enters the condensate tank in the plant to be reused later. The remaining steam passes through the turbine. The single effect absorption chiller operates at capacity in parallel with the campus steam load.

4.4.6 Baseline December model

The energy plant is modeled using the actual configuration and steam production data in December. This provides a baseline for fuel consumption, energy efficiency, and exergy efficiency of the plant in the winter. No turbine is present and all the steam produced passes through the PRV. Steam is produced in the boiler at a pressure of 977 kPa and drops to 515 kPa after the PRV. The absorption chiller is not required to meet chilled water needs during winter and therefore is not modeled in this case study.

4.4.7 Case study 5 – December model with turbine

A load following steam turbine is modeled using December steam production data. Inlet steam pressure is 977 kPa and steam exhaust pressure is 515 kPa. All the steam produced by the boiler is passed through the turbine, at the conditions shown in Table 4.1, instead of the PRV. The absorption chiller is not required to meet chilled water needs during winter and is not modeled.

4.4.8 Case study 6 – December model with turbine at increased pressure

The energy plant is modeled using steam production data in December. A load following steam turbine is modeled using conditions shown in Table 4.1. Steam is produced in the boiler at an increased pressure of 1481 kPa and drops to 515 kPa after the turbine. The absorption chiller is not required to meet chilled water needs during winter and is not modeled.

Table 4.2. Case studies and their key features.

	Month	Turbine	Steam P_{inlet} (kPa)	Steam P_{exit} (kPa)	Chillers
Summer Baseline	July	No	977	515	Single effect
Case Study 1	July	Yes	977	515	Single effect
Case Study 2	July	Yes	1481	515	Single effect
Case Study 3	July	Yes	977	515	Single, Double effect
Case Study 4	July	Yes	1481	515	Single, Double effect
Winter Baseline	December	No	977	515	None
Case Study 5	December	Yes	977	515	None
Case Study 6	December	Yes	1481	515	None

4.5 Results and Discussion

Fuel consumption calculated by the TRNSYS model is compared with actual fuel consumption data provided by the energy plant. Fuel consumption at the plant is not measured daily, and weekly trends are used for the sake of this analysis. The hourly cost of fuel can be expressed as the following, where C_{BDMT} is the cost per BDMT:

$$C_{fuel} = \dot{m}_{fuel} * C_{BDMT} \tag{4.8}$$

Using equation 4.8, the hourly fuel costs to produce steam for each model are shown below. Figure 4.3 displays the December fuel consumption of the system determined by TRNSYS with actual fuel consumption recorded at the energy plant. The model predicts fuel consumption closely, with some variation due to variables such as changes in moisture content that cannot be accounted for. Since the steam turbine is load following, fuel consumption is not impacted by its operation.

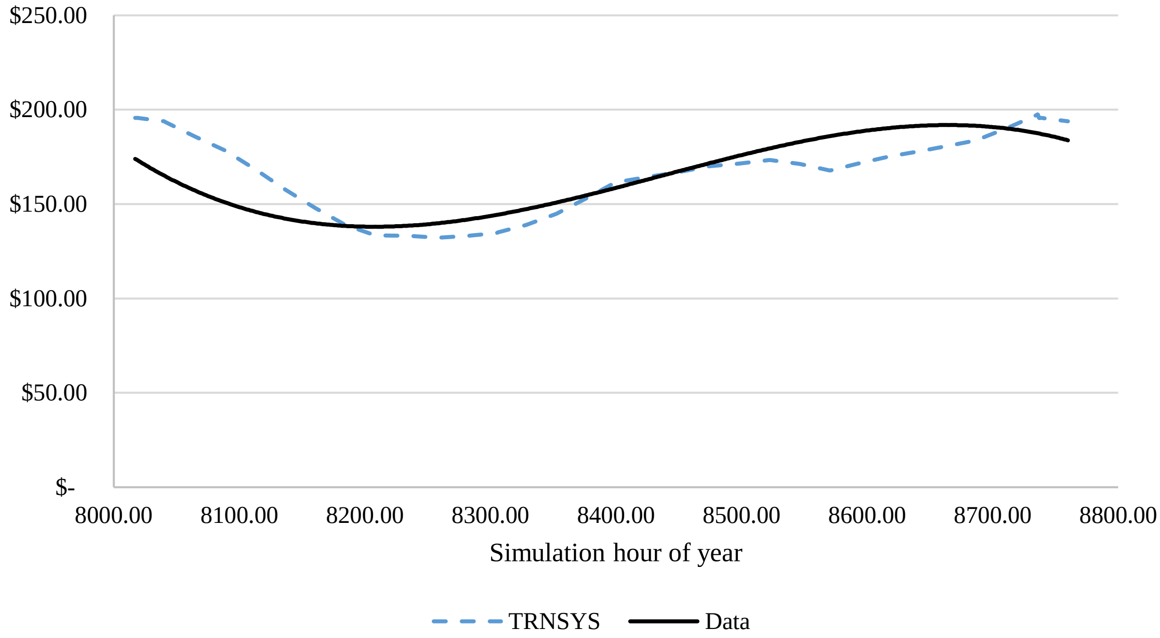

Figure 4.3. Hourly fuel costs for December 2015.

Where the December fuel consumption fluctuated as the boiler met heating demand, fuel consumption in July, shown in Figure 4.4, is mostly steady. The case studies with only a single effect chiller in operation have slightly higher fuel consumption than the actual data provided. Steam flow requirements are calculated independently for the absorption chiller components in TRNSYS and both the single and double effect chillers consume slightly more steam than in the model compared to actual conditions, which is reflected in the difference in fuel consumption between the single chiller model and actual data. Case studies where both the single and double effect chillers are running show substantial increase in fuel consumption compared to where just the single effect is in operation as cold production is significantly increased. Figure 4.3 and Figure 4.4 allow for the baseline fuel consumption to be determined when investigating the economic impact of installing the steam turbine.

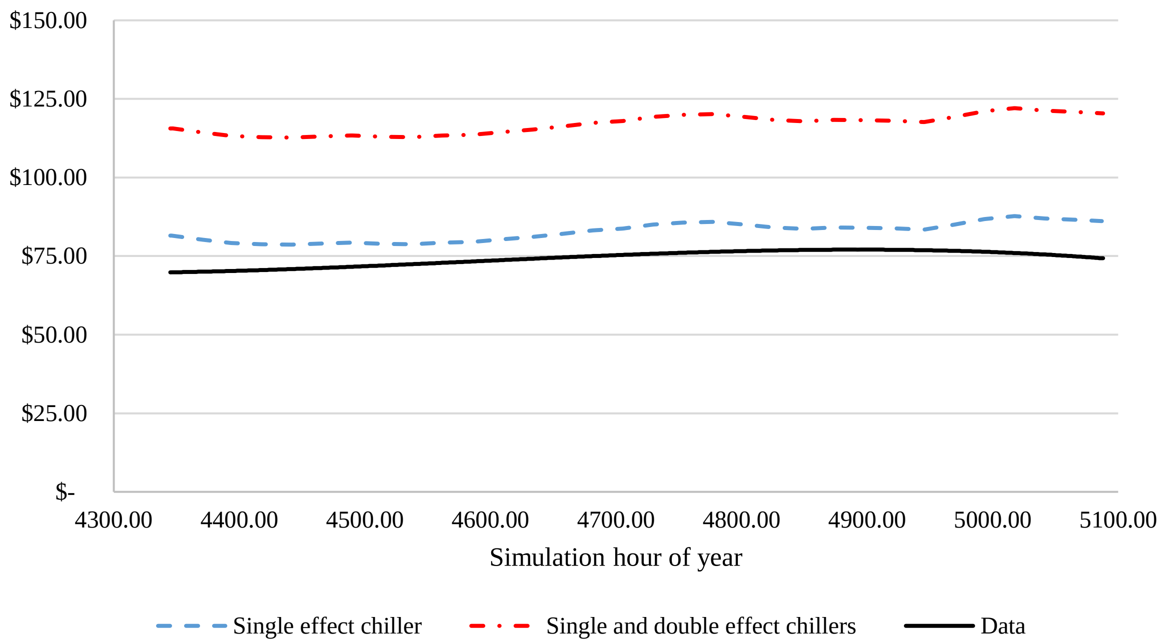

Figure 4.4. Hourly fuel costs for July 2015.

The hourly fuel consumption costs for each case study can be summed to determine the monthly costs. Figure 4.5 shows the monthly fuel costs for each case study compared to the baseline fuel costs. The new operating costs after installing a turbine are determined by subtracting the profit from the sale of electricity produced by the turbine, $C_{turbine}$, from the predicted fuel cost of the TRNSYS model as follows:

$$C_{operating} = C_{fuel} - C_{turbine} \tag{4.9}$$

The installation of a steam turbine reduces operating costs significantly in all case studies. Costs are further reduced when steam pressure is increased. Monthly costs are lowest for case studies 1 and 2, when steam production in the summer is at its lowest. The turbine has the least effect on operating costs in case studies 3 and 4, where the double effect chiller is also operating. This is due to steam being diverted from the turbine to produce cooling instead. The largest impact is found in case studies 5 and 6 as steam production is at its largest during the winter and more steam is passing through the turbine for power production.

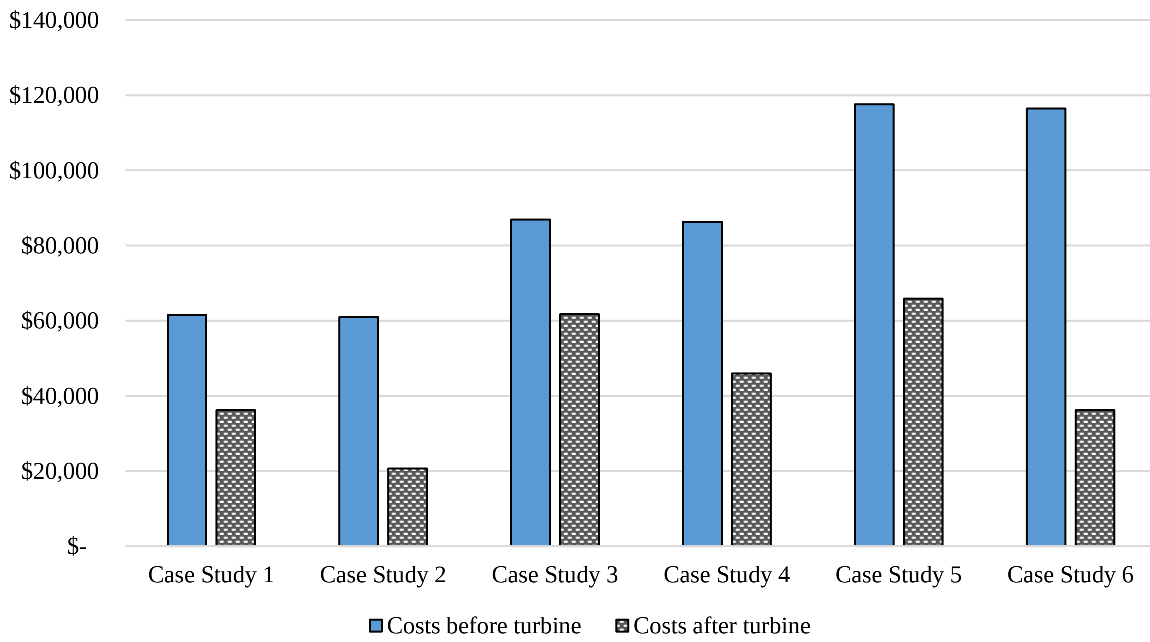

Figure 4.5. Monthly operating costs of each case study compared to the baseline costs.

Figure 4.6 shows the energy and exergy efficiency improvements in case studies 1 and 2. Energy efficiency increases 3-4% with the introduction of a steam turbine, which is to be expected as usable work is being produced through the pressure drop of steam as opposed to passing through the PRV. Energy efficiency in case studies 3 and 4 increases 20% in Figure 4.7 with the addition of a double effect chiller as well as the turbine. Figure 4.8 shows that case studies 5 and 6 are the most energy efficient, where steam and power generation are at their peak. Energy efficiency does not increase with a rise in boiler steam pressure however in all models. This is due in part to increased pumping requirements and requires additional research in the future. Exergy efficiency increases in every case study, but does not share the sharp increase with energy efficiency in case studies 3 and 4. This is due to one of the underlying principles of exergy: that work has more value than heat on an exergetic level.

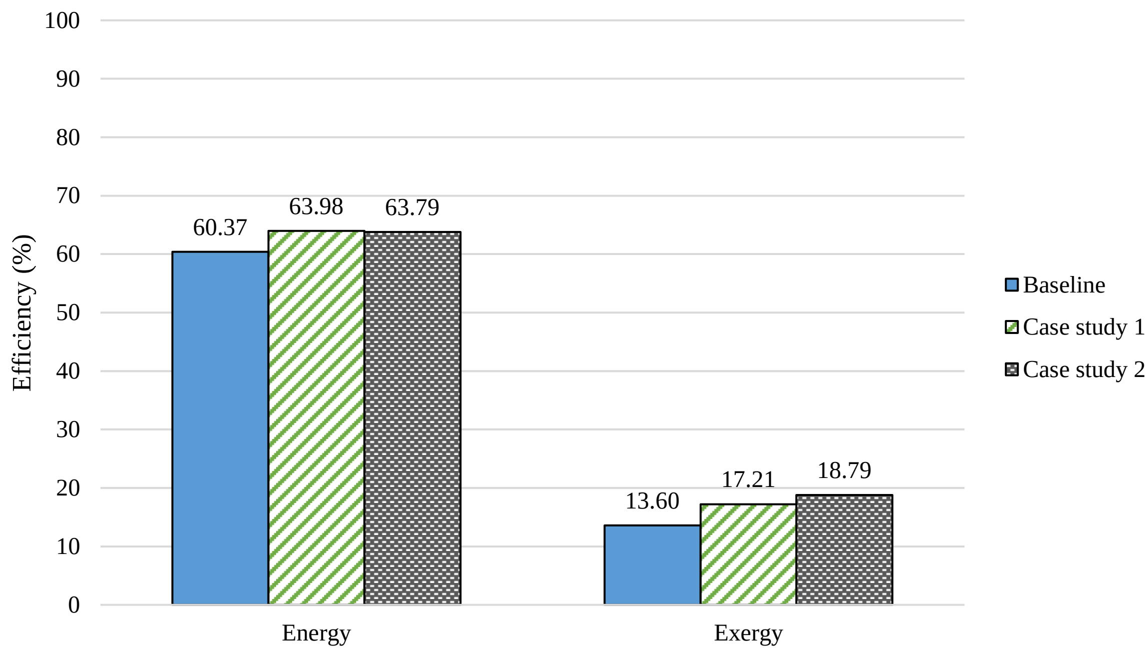

Figure 4.6. Average system energy and exergy efficiency with a single effect chiller for July.

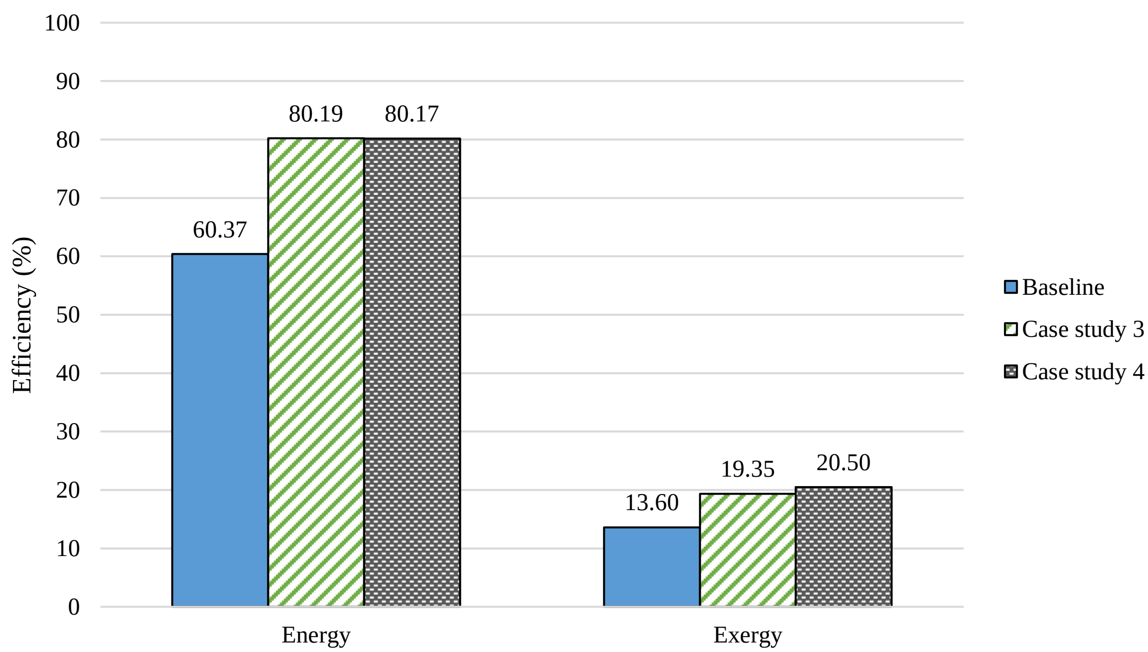

Figure 4.7. Average system energy and exergy efficiency with single and double effect chillers for July.

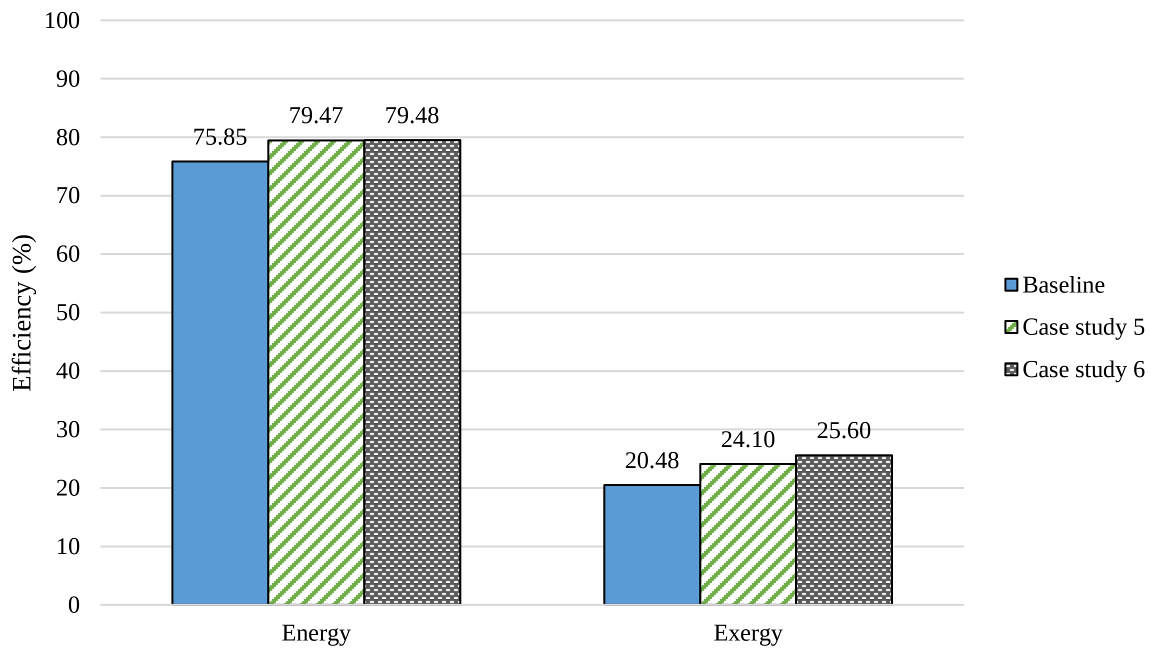

Figure 4.8. Average system energy and exergy efficiency for December.

4.6 Conclusions

An investigation into the improvement of the UI energy plant through the installation of a steam turbine and double effect absorption chiller has been presented. Six different case studies are compared using TRNSYS modeling software. Fuel consumption, energy efficiency, and exergy efficiency of each case study are calculated. The installation of a load following, backpressure steam turbine to replace the PRV as the primary means of reducing steam pressure has the potential to result in significant economic savings with minimal modifications needed. Increasing steam pressure through the boiler further increases these savings. Economic savings are reduced however if a double effect chiller is installed due to the increased fuel consumption.

Using biomass to meet campus energy requirements allows for UI to have a sustainable fuel source. There are still opportunities however to improve system performance. Installation of a turbine can increase energy efficiency by 3-5% during the peak summer and winter seasons. To realize maximum potential improvement in energy efficiency, steam pressure through the boiler should be increased and a steam turbine should be installed. Bringing a double effect chiller online in addition to the current single effect chiller has the largest impact on the system, increasing energy efficiency by 20% during the summer at the expense of increased operating costs due to the lost potential for power generation. The user must decide which provides the greatest benefit: power generation or the production of chilled water. Exergy efficiency also increases 4-7% with each case study. The double effect chiller does not have the same impact on exergy efficiency as it does on energy efficiency, since work has a much higher value than heat at the exergetic level.

Expanding the scope of this study further to include the chilled water TES tank and piping network could reveal additional areas of improvement. Further improvements can be had through a more advanced turbine configuration to produce even more power; however, this would result in a much larger capital investment and extensive modification to the existing plant. More information would be needed on the electricity requirements of campus as well. A more in depth economic analysis to determine initial capital costs and potential rate of return of additional equipment can give better insight into the feasibility of generating power at the UI main campus energy plant.

Chapter 5: Advancement of Environmental Sustainability in Institutional Buildings Through Waste to Energy Technology: Case Study

Forthcoming in *Energy for Sustainable Development*

5.1 Abstract

Disposal of municipal solid waste in landfills has an excessive impact on the environment (soil, air, water). This can be reduced drastically by incinerating the waste to generate energy. The energy can then be used to generate steam for heating or electricity while MSW is eliminated from harming the environment. The principle objective of this study is to investigate the feasibility of utilizing waste-to-energy (WTE) technology at the district energy plant for the main campus of University of Idaho located in Moscow, Idaho, USA. An assessment of production, composition, and the energy content of the solid waste on campus is conducted. It is found that the waste generated on campus can only support 2% of steam requirements. Expanding the collection of municipal solid waste (MSW) to the surrounding community would be meet 42% of steam production requirements. The heating value for the MSW generated on campus is 13.67 MJ/kg, slightly above the national average. The use of WTE to produce steam has the potential to save over $500,000 annually over the biomass fuel currently used, and over $1.5 million compared to natural gas exclusively. Besides the financial benefits of WTE, environmental sustainability increases drastically by eliminating MSW from landfills.

5.2 Introduction

Sustainable waste management practices are essential in today's modern world. It is estimated that over 60% of municipal solid waste generated in the United States is landfilled [75]. The seventy seven waste-to-energy plants in the US have been operating for decades, most being built between 1980-1995, and process less than 8% of the MSW generated nationally [76]. In comparison, China has built sixty new WTE plants within the past five years to reduce its use of landfills while, Japan, Singapore, and many European nations have virtually eliminated the need for landfilling through the extensive use of recycling, composting, and WTE technology. This indicates that WTE applications are a relatively untapped resource in the United States.

Utilizing biomass as an energy source is generally considered to be carbon neutral, since the CO_2 released during combustion was originally absorbed during its growth through photosynthesis [9]. A MSW fuel supply can have varying percentages of biomass in addition to plastics and other fossil fuel based substances and is therefore only partially carbon neutral. Increased recycling of plastics and other non-renewables with pre-burn processing would further offset carbon emissions. Even though there are greenhouse gas contributions from a WTE facility, those gases are at least partially offset by the reduction in methane produced from the MSW decomposition in landfills. Greenhouse gas emissions are further reduced by eliminating the need to transport MSW to a distant landfill. It is estimated that approximately 1 metric ton of CO_2 emissions are saved for each ton of MSW diverted to a WTE facility rather than landfilled [77].

To minimize the environmental impacts of MSW, efforts must be taken before entering landfills. Recyclable and compostable materials should be removed, preferably at the source, to reduce the quantity and transportation costs of the waste being produced. The remaining waste is then suitable for combustion/incineration in the WTE process, in which waste is commonly fed into a high temperature furnace to generate steam to drive turbine generators for the production of electricity [77]. Thermal methods of treating MSW have been outlined by Lombardi, et al., including incineration, gasification, and pyrolysis [78]. Incineration with energy recovery via steam cycles is the most common form of treatment.

Steam can also be used in district heating applications as well in a combined heat and power (CHP), or cogeneration configuration. Ryu and Shin have investigated the use of WTE technology in South Korean CHP plants [79]. They showed an increase in the lower heating value of the MSW as the percentage of food waste, and thus moisture content, decreased. Furthermore, they showed that small scale WTE plants that produce only heat have higher energy efficiencies than plants producing both heat and power. Pavlas et al. showed that more advanced systems with higher operating conditions are needed to improve electrical efficiency when there is insufficient heat demand in cogeneration cycles [80] . Fruergaard et al. have assessed the use of MSW in two Danish CHP plants [81]. They emphasize the importance of MSW fuel composition in determining the system performance of district heating networks and that assumptions based on national averages may be inadequate.

The main University of Idaho (UI) campus located in Moscow, Idaho, USA utilizes a district energy plant to provide heating and cooling to most of campus. 95% of steam requirements are met using biomass fuel in the form of wood chips sourced from the waste streams of regional logging industries. Natural gas is used to supplement the biomass boiler during peak loads. To further increase the sustainability footprint of UI and reduce the need for fossil fuels, an investigation is presented on the feasibility of implementing WTE technology on campus. The composition, heating values, and generation rate of MSW on campus is determined. The UI steam requirements and waste generation is compared with similarly sized WTE sites that are already in operation. Finally, economic and environmental impacts of utilizing WTE are investigated.

5.3 Case Study: University of Idaho Energy Plant

Heating and cooling are distributed in the University of Idaho, Moscow, Idaho campus through a district heating and cooling (DE) system. The DE system is composed of a biomass boiler for steam production that is primarily used for heating. The district energy plant at the UI provides heating for 63 and cooling for 46 buildings in Moscow campus. The 10.4 MW biomass boiler was installed in the 1980s which utilizes woodchips as fuel for generating the steam.

The UI district energy plant produced 118 million kg of steam in 2016 to support campus heating and cooling needs, averaging of 13,600 kg per hour. 95% of the steam was produced using wood chips and the other 5% of needs were met using natural gas. The University of Idaho produced 1116 metric tons (1230 short tons) of solid waste in 2016. Of this total, 296 metric tons were recycled, 47 metric tons were composted, and the remaining 773 metric tons were landfilled which could be a potential resource for WTE in the UI Moscow campus.

5.4 Analysis

5.4.1 Assessment of MSW

Part of the solid waste produced in the UI Moscow campus ends in the landfill. The landfilled portion of the MSW is the potential fuel source available for WTE. The energy available from solid waste can be affected by its composition. As such, recycling rates and composting efforts will have an impact on the energy available. Recycling can help remove non-renewable materials from the waste fuel supply which would in turn make the process more carbon neutral. This has an impact on the potential heating value of the MSW fuel. Efforts to increase recycling will generally lower the heating value of the fuel by removing high energy content items like plastics, while composting increases the heating value by removing food and other biomass with high moisture content [79]. This is demonstrated in Figure 5.1, where the moisture content in a fuel comprised of biomass, such as food waste and other compostable material found in MSW, has a significant impact.

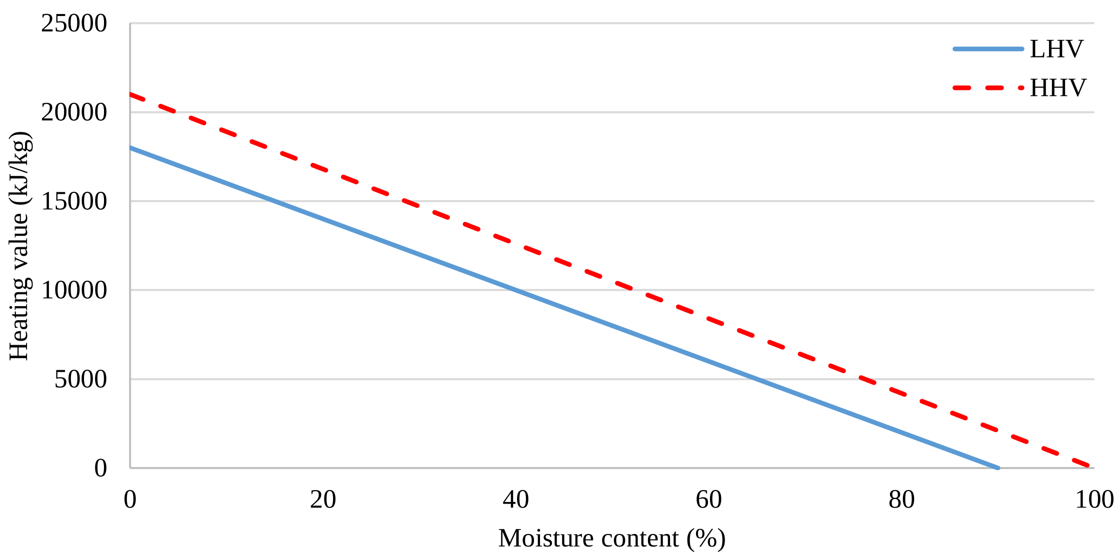

Figure 5.1. Lower and higher heating values of biomass versus moisture content [27].

5.4.2 Waste Characterization

The University of Idaho has many different types of facilities with many functions on its campus and as such produces a diverse range of waste streams which can affect the performance of a WTE facility. All waste streams except dining services are processed by UI before being collected by the municipal landfill. In 2009 UI conducted an extensive study to determine the composition of the waste being produced on campus [82]. The study consisted of a series of surveys where waste was collected from dumpsters for a variety of different buildings on campus such as office and classroom buildings, residence halls, the library, greenhouses, etc. Dining services were excluded at the time due to a separate study characterizing the potential for composting benefits from the dining facilities. This information is included in this study however to analyze the energy potential on campus.

Waste items were sorted and weighed into the categories provided in Table 5.1 below. The categories consist of recyclables that are currently accepted by the UI recycling facilities, compostable items such as food waste and paper towels, and waste that must be landfilled. There are other types of trash produced on campus such as toxic material including oil containers, aerosol cans and medical waste, but this type of waste is highly regulated and has programs in place to be properly disposed of. It accounts for a negligible portion of the overall campus waste production and is neglected in this study. Landfill material made up 39% of the items found in the dumpsters by weight, accepted recyclables accounted for 38% of the material, and compostable material 23%.

Table 5.1. The UI Moscow campus waste composition categories in 2009 [82].

Category	Percentage by Weight (%)	Description
Accepted recyclables	38	Plastics – #1 and #2
		Cardboard
		Paper – white ledger, mixed, paperboard
		Newspaper
		Aluminum/Tin
Compostable	23	Food waste
		Organics – paper towels, plates, cups, etc.
Landfill	39	Plastics – #3-#7
		Glass
		Construction/demolition material
		Electronic/hazardous waste
		Other metals
		Trash
		Other plastics – bags, non-labelled containers

The composition on MSW resources has a significant impact on it energy potential. General estimates are available from the U.S. Environmental Protection Agency (EPA) at the national level [75]. More detailed information, such as types of plastic, is difficult to attain at this scale. MSW characterization studies from eleven US states have been compared by Staley and Barlaz, who suggest that sample collection at a certain site via sorting and weighing can provide a better understanding of MSW composition [83]. This is particularly useful since MSW varies between locations. Table 5.2 outlines MSW characterizations for EPA estimates, statewide samples collected by Staley, and the UI. The UI estimate is based on the dumpster survey outlined in Table 5.1 and data provided by the UI Facilities. Material such as yard trimmings and durable goods, which includes items such as appliances and electronics, are not landfilled at the UI.

The MSW composition determined at the UI is similar to that found nationally and from other sites. The dumpster survey originally focused on recyclable content and did not categorize many items found that could not be easily recycled or composted. This leaves a much larger percentage of the MSW unclassified in this study compared to the other sources. Paper and cardboard products make up 32% of the total waste. Food waste and compostable material/organics such as paper cups account for 26%. Plastics and metals make up 12% and 7%, respectively. Figure 5.2 depicts the MSW combination at the UI, Moscow campus.

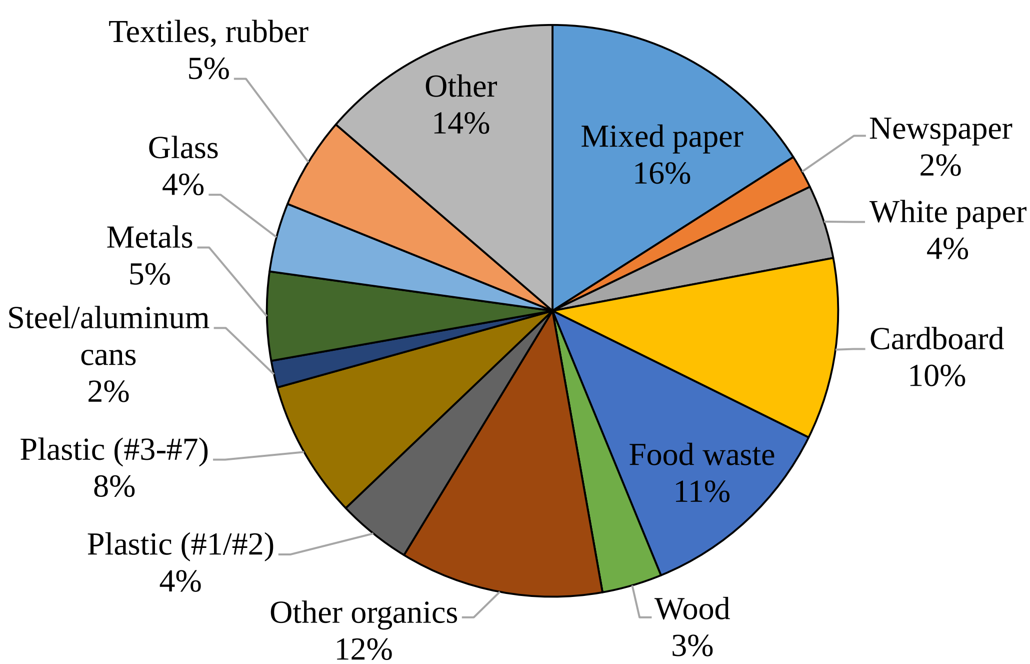

Figure 5.2. Estimated MSW composition by weight generated at UI.

Table 5.2. MSW characterization [75], [82], [83].

Category	EPA (%)	Staley (%)	UI (%)
Paper/cardboard			
Mixed paper	-	-	15.9
White paper	-	-	4.2
Newspaper	-	-	1.9
Cardboard	-	-	10.3
Total	26.6	37	32.3
Biomass/organic			
Food waste	14.9	13.6	11.5
Wood/lumber	6.2	3.4	3.4*
Yard trimmings	13.3	5.9	0
Other organics	-	2.7	11.5
Total	34.4	25.6	26.4
Plastics			
Plastic #1/#2	-	-	4.18
Plastic #3-#7	-	-	7.8
Total	12.9	13.2	12
Metals			
Steel/aluminum cans	-	1.7	1.52
Other metals	-	5	5*
Total	9	6.7	6.5
Glass	4.4	3.4	3.9
Textiles/rubber	9.5	5.2	5.2*
Durable goods	-	6.5	0
Other	3.2	2.4	13.7
Total MSW	100	100	100

5.4.3 MSW Energy Content

With the composition of the MSW generated at the UI, the energy content can be calculated. Table 5.3 lists typical heating values for common items found in MSW [84]. Organic materials, especially food waste, often have low heating values due to high moisture content. Material that does not combust, such as metal and glass, does not have a heating value and is not included.

Table 5.3. Higher heating values for common solid waste types [84].

Solid Waste Material	HHV (MJ/kg)
Textiles	14.33
Rubber	27.93
Leather	14.95
Wood	10.38
Food waste	5.4
Yard trimmings	6.23
Newspaper	16.61
Corrugated cardboard	17.13
Paper	6.96
Other/Landfill	21.6

Plastic often makes up a large portion of MSW even after recycling efforts and generally has a very high heating value (HHV) when compared to other products. Table 5.4 outlines HHVs for each type of waste plastic. It has been recognized by multiple groups that the values obtained by the EIA are too low. For this study, the average HHV from the other studies are used for calculations, however the EIA values are provided for reference.

Table 5.4. Higher heating values in MJ/kg for plastics reported in the literature [84]–[87].

Plastic	EIA	Columbia	CCNY	Franklin	Used in this study
Polyethylene Terephthalate (PET) #1	21.3	23.9	24.4	24.7	**24.3**
High-density polyethylene (HDPE) #2	39.5	44.3	40.6	46.5	**43.8**
Polyvinyl chloride (PVC) #3	17.1	19.2	24.4	18.3	**20.6**
Low-density polyethylene/Linear low-density polyethylene (LDPE/LLDPE) #4	25	44.3	44.1	46.3	**44.9**
Polypropylene (PP) #5	39.5	44.3	44.1	46.4	**44.9**
Polystyrene (PS) #6	37	41.5	40.6	41.9	**41.3**
Other #7	21.3	n/a	40.6	n/a	**40.6**

The energy content for each waste type can be written as the following:

$$E_w = \frac{m_{fr}}{100\ \%} * HHV \qquad (5.1)$$

Where E_w is the energy content and m_f is the mass fraction previously calculated in Table 5.2. The energy content for each material is summed below in Table 5.5 after applying equation 5.1. The HHV for plastics #1 and #2 are averaged together, as well as plastics #3-#7 and textiles/rubber. A HHV of 13.67 MJ/kg is estimated based on the composition of the waste generated at the UI. This is consistent with, but slightly higher, than heating values found in literature [18], [78], [84], [88]–[90]. This is most likely due to efforts made by the UI to compost food waste and yard trimmings. A more extensive survey of the waste generated to identify uncategorized material would provide a more precise heating value. Each category's contribution to the total energy value of the MSW is shown in Figure 5.3. Paper and cardboard products make up about 25% of the total energy content of the MSW. Organic material like food waste makes up a large percentage of MSW by weight, but contributes little as a potential fuel source. 33% of the energy content is provided by plastic. The uncategorized material, textiles, and rubber account for 29%.

Table 5.5. Estimated energy content of the MSW generated on the UI Moscow campus in 2009.

Category	m_f	HHV (MJ/kg)	E_w (MJ/kg)
Mixed paper	15.9	6.96	1.11
White paper	4.2	6.96	0.29
Newspaper	1.9	16.61	0.33
Cardboard	10.3	17.13	1.71
Food waste	11.5	5.4	0.65
Wood	3.4	10.38	0.31
Yard trimmings	0	6.23	0
Other organics	11.5	5.4	0.65
Plastic (#1/#2)	4.18	35.36	1.49
Plastic (#3-#7)	7.8	39.81	3.18
Steel/aluminum cans	1.52	0	0
Metals	5	0	0
Glass	3.9	0	0
Textiles, rubber	5.2	19.07	0.99
Other	13.7	21.6	2.96
Total	100		**13.67**

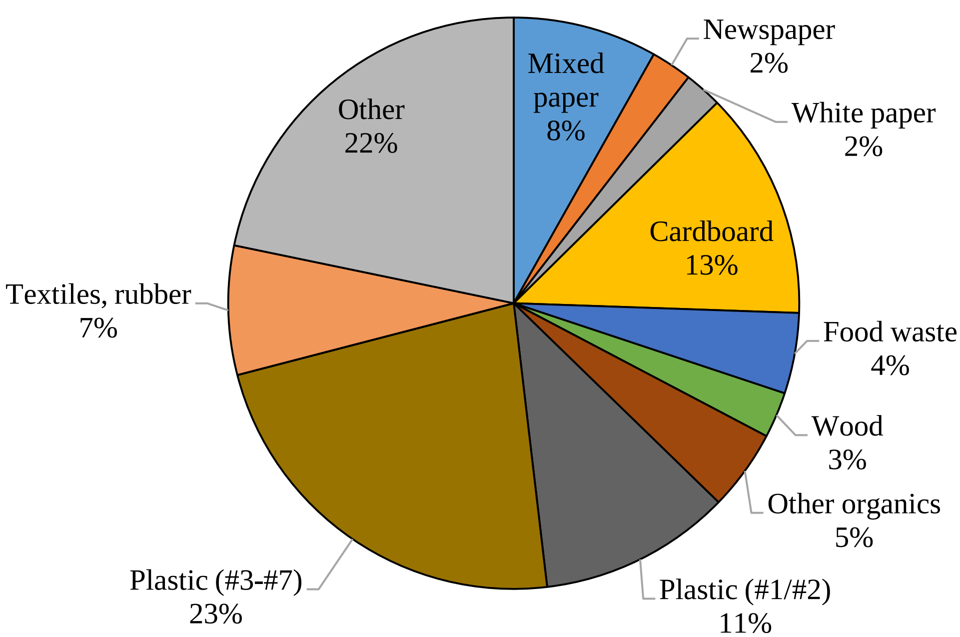

Figure 5.3. Breakdown of MSW energy content.

5.4.4 Fuel Scenario Options

The UI district energy plant produced 118 million kg of steam in 2016 to support campus heating and cooling needs. 95% of the steam was produced using wood chips and the other 5% of needs were met using natural gas. The addition of MSW to the fuel supply would be inadequate to replace the use of wood chips entirely to meet campus energy demands. However, if MSW was collected from the surrounding community as well, a significant amount of steam requirements could be met. According to the most recent estimates, the 39,000 residents in the community produce 16000 metric tons (17600 short tons) of MSW annually [91]. This estimate includes MSW generated by the UI Moscow campus. The composition of this MSW stream is not known, therefore the energy content of the MSW produced in the surrounding community is assumed to be 12.18 MJ/kg, based on typical values from the EIA [84].

There are significantly fewer WTE facilities in the US that produce only thermal energy with steam compared to those producing heat and electricity. Table 5.6 below compares the potential capacity for UI when compared to similar WTE thermal energy plants. It is of some interest that the amount of steam produced per unit of MSW fuel is similar at each facility. This can be used to estimate a reasonable size for a WTE system at the UI by accounting for discrepancies in the MSW composition and varying efficiencies for each plant. Taking the average value for each facility results in 3.11 kg of steam per 1 kg of MSW fuel consumed. If the same ratio is assumed for a potential WTE plant at UI, then a steam capacity of 5,700 kg/hr can be estimated based on the amount of MSW fuel available.

Table 5.6. Comparison of thermal energy WTE facilities [76], [92].

Location	Serviced Population	Waste Capacity (1000 kg/day)	Boilers	Steam Capacity (kg/hr)	Steam Produced per kg Waste (kg)
Huntsville, AL	277000	626	2	81000	3.11
Fosston, MN	90000	73	2	9500	3.15
Red Wing, MN (inactive)	44000	87	2	6800	1.88
Hampton, VA	180000	218	2	29900	3.3
Alexandria, MN[1]	42000	218	3	34500	3.8
James Madison University, VA	122000	181	2	25900	3.42
UI Moscow campus only	9350[2]	1.92	-	550[3]	3.11[4]
UI and surrounding area	39000[5]	44	-	5700[3]	3.11[4]

1. The Pope-Douglas WTE facility in Alexandria, MN processes significant industrial waste.
2. Based on student body population.
3. Determined from steam produced per kg of waste multiplied by the waste capacity.
4. Based on average of other WTE locations.
5. Based on census data [93].

5.4.5 Financial Comparison: Fuel Options

Fuel prices are typically stable throughout the year. The average price of wood chips was $56.22 per bone dry metric ton in 2016, while the cost for natural gas averages $6.00 per deca-therm. Monthly fuel consumption and steam production data for the 2015 fiscal year are shown in Table 5.7. The cost of wood chips is slightly higher during the winter months, when demand is higher. Using natural gas exclusively to produce steam would cost $2.1 million annually. Wood chip fuel costs $1.1 million in comparison, resulting in over $1.0 million in savings for the UI. This is the reason wood chips are used for nearly all steam requirements throughout the year.

Table 5.7. Monthly fuel and steam data for FY2015.

Month	Steam by Wood (1000 kg)	Wood Cost (per 1000 kg)	Steam by Gas (1000 kg)	Gas Cost (per 1000 kg)	Total Steam (1000 kg)	Avg Cost (per 1000 kg)
Jul	8376.02	$ 9.44	0.00	$ -	8376.02	$ 9.44
Aug	8460.41	$ 7.67	0.00	$ -	8460.41	$ 7.67
Sep	7237.62	$ 7.96	547.94	$ 17.26	7785.56	$ 8.61
Oct	7949.84	$ 7.23	2155.63	$ 17.17	10105.47	$ 9.35
Nov	12083.49	$ 8.86	331.71	$ 20.97	12415.20	$ 9.19
Dec	11734.90	$ 9.28	1648.49	$ 17.55	13383.39	$ 10.30
Jan	12746.41	$ 10.01	296.83	$ 17.61	13043.25	$ 10.18
Feb	10264.81	$ 8.11	19.07	$ 17.75	10283.88	$ 8.13
Mar	10384.56	$ 8.82	0.00	$ -	10384.56	$ 8.82
Apr	9340.39	$ 7.98	1180.35	$ 17.64	10520.74	$ 9.06
May	9973.15	$ 8.66	6.85	$ 17.53	9980.00	$ 8.67
Jun	7547.79	$ 8.14	1.48	$ 17.44	7549.26	$ 8.14
Total	116099.39	$ 8.61	6188.36	$ 17.60	122287.75	$ 9.07
Overall %	95%		5%			

Implementing a WTE system would result in even further savings for the energy plant, as it is assumed that there would not be a cost for MSW fuel. It is also assumed that the operating costs for the WTE system would be similar to the current plant, however it should be noted that efforts would need to be made to sort the incoming MSW for recycling and other unwanted material. For determining the financial impact, MSW generation for the surrounding area is used. In 2016 the UI paid almost $90,000 in tipping fees to dispose of MSW generated on the campus. Using WTE should eliminate this fee as well as reduce costs for the community from collection and landfilling.

5.5 Results and Discussion

The outcomes of the feasibility study for a waste to energy in different scenarios for the steam plant at UI are reported in the different environmental and financial categories.

5.5.1 Different Scenarios

Using wood chips, natural gas, and MSW for the UI steam plant are defined in the different scenarios. Figure 5.4 shows the potential fuel mix for the UI energy plant if MSW resources are used in different scenarios. If only the MSW generated on the UI Moscow campus is utilized, 2% of the current steam load could be met. Expanding the collection of MSW to the surrounding area could meet 42% of the load, based on the 5700 kg/hr of steam production potential from MSW. It is assumed that natural gas would continue to be used to meet about 5% of needs due to maintenance and peak loads. A significant additional source of MSW fuel could be available if negotiations can be made with the nearby city of Pullman, Washington. With a similar population, it resides only 15 km away across the state border. This could be advantageous for both communities, as MSW generated in Pullman must travel approximately 450 km before reaching a landfill [94]. The ability to utilize MSW as a fuel source would increase capacity for the UI energy plant without increasing fossil fuel consumption and reduce its environmental impact.

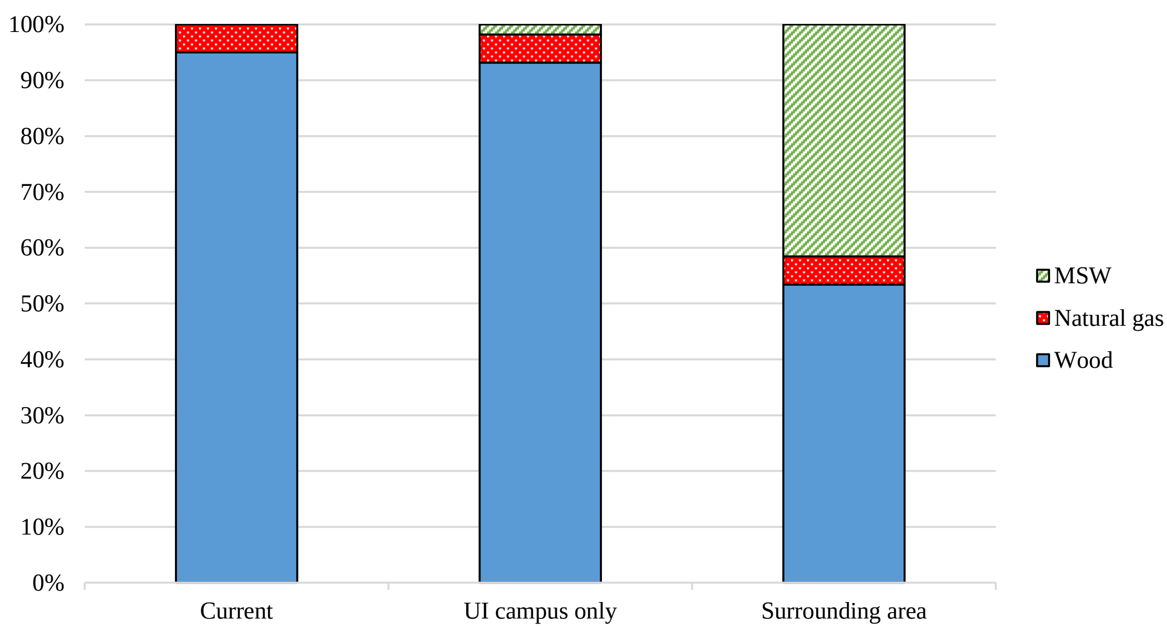

Figure 5.4. Possible fuel scenarios at the UI energy plant.

5.5.2 Financial Comparison

By having the different scenarios of different fuel combination as mentioned above, the fuel cost for each option is different. Figure 5.5 shows the cost per 1000 kg of steam produced for each fuel type. If the MSW supply is consistently 42% of the wood chip supply, the energy plant could potentially save $416,000 annually, based on the 118 million kilograms of steam produced and average fuel costs in 2016. If tipping fees are eliminated, savings could be over $500,000. Compared to using natural gas for all steam production, savings are over $1.5 million if MSW fuel is used together with wood chips. It should be clarified that the study is only investigating the cost of the fuel. The initial investment for installing the needed equipment for WTE is not covered here since sizing the furnace for WTE is a vast study by itself.

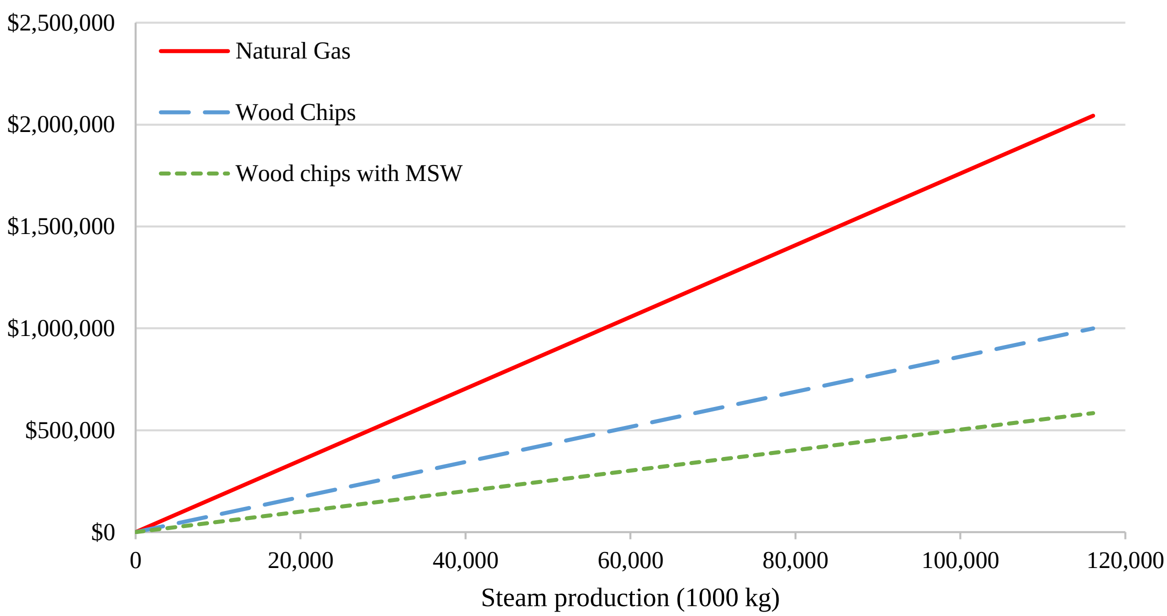

Figure 5.5. Fuel costs versus steam production for each fuel type.

5.5.3 Environmental Sustainability Improvement

There are three major ways that the environmental impact of implementing WTE can be measured:

- Landfill protection
- Transportation
- Greenhouse gas (GHG) reduction

Diverting MSW from the landfill has several benefits such as extending the useful life of the existing landfill, reducing potential long-term impacts on the ground water near the landfill, and the reduction of GHGs. It has been estimated by Themelis and Ulloa that 0.149 metric tons of methane are generated by every metric ton of MSW in landfills [95]. It is also estimated that approximately 1 metric ton of CO_2 emissions are saved for each ton of MSW diverted to a WTE facility rather than landfilled [77]. Thus, a WTE facility at the UI Moscow campus could prevent 2384 metric tons of methane and 16,000 metric tons of CO_2 from being released to the atmosphere. This would help offset the increased CO_2 generation at the energy plant when combusting MSW instead of wood chips.

In addition to the direct benefits of diverting MSW from landfill, equivalent CO_2 reduction is estimated due to reduced transportation distances. Currently, MSW generated in Moscow is transported about 190 km by rail to the landfill. CO_2 equivalent emissions from rail transport are estimated at 0.025 kg per imperial ton-mile [96]. Using this estimate for 16,000 metric tons of MSW, approximately 53.6 metric tons of CO_2 could be offset annually. CO_2 generation from the collection of MSW by truck is assumed to be unaffected.

The UI Moscow energy plant almost exclusively uses biomass fuel, which is carbon neutral and results in incredibly low CO_2 emissions. The use of WTE, which would typically result in a reduction in carbon emissions compared to fossil fuels, would increase emissions at the energy plant. This is because only the biogenic portion of MSW fuel can be considered carbon neutral, whereas the non-biogenic portion such as plastics, is fossil fuel derived. The EIA estimates that the biogenic portion of MSW makes up 56% of the energy content while non-biogenic MSW makes up 44% [84]. They also estimate CO_2 generation rates of 53.12 kg/1000 ft^3 of natural gas and 2617.68 kg/short ton of MSW burned to produce energy [97]. These values can be used to predict net CO_2 emissions at the energy plant based on annual natural gas consumption and MSW availability, shown in Table 5.8. Since the goal is to investigate net emissions into the environment, only the CO_2 generated from the non-biogenic MSW is accounted for. Net CO_2 emissions would increase by 4217 tons annually. Recycling efforts to reduce the non-biogenic material from the MSW would reduce this amount. It is still assumed that natural gas would be used at the same rate as well. This increase in CO_2 emissions must be balanced against the reduction of 2384 tons of methane emissions, which has a substantially larger global warming potential than CO_2. Table 5.8 depicts emitted CO_2 for each scenario in different stages.

Table 5.8. Net CO_2 emissions for each scenario.

	Current fuel mix (Metric tons)	Proposed fuel mix (Metric tons)
Natural gas	1306	1306
Landfill	16000	0
Rail transport	53.6	0
WTE	0	20271
Total	17359.6	21577

5.6 Conclusions

A feasibility study for a WTE steam plant at the UI Moscow campus was conducted. The composition of the MSW generated on campus was determined. It is found that the HHV of the MSW is 13.67 MJ/kg, which is slightly higher than that estimated by the EIA. This is most likely due to efforts by the UI to compost material such as food waste and yard trimmings. MSW generation on campus is inadequate to support steam production requirements and the surrounding community would be needed to contribute. It is estimated that this would support 42% of steam production. If the UI does not need to purchase MSW, the energy plant can save $500,000 annually in fees and fuel costs by reducing the amount of wood chip fuel required. Compared to using only natural gas, introducing MSW fuel would save over $1.5 million per year.

The energy content in MSW varies significantly with composition. Biogenic material such as food waste has a high moisture content, significantly reducing the heating value. Plastics on the other hand have very large heating values. Sorting and processing MSW before combustion increases recycling rates and has long term environmental benefits, but impacts the performance of a WTE plant by reducing the energy content of the fuel. The wood chip fuel used at the energy plant already is itself a waste stream from nearby lumber mills. This puts UI in a unique position to further enhance its sustainability footprint by making use of two local waste streams. The proposed energy plant would not be as dependent on the energy content and generation of MSW generated as current large scale WTE plants, while not being as affected by any future changes in the supply or cost of wood chips.

Redirecting MSW for use in WTE reduces our dependence on landfills. The impact on the environment is lessened through a reduction in methane generated in landfills, transportation requirements, and the potential for toxic material to leak into ground water sources. The successful operation of a WTE plant at UI would be unique by demonstrating its potential in less populated areas while bringing significant economic benefits. Further than economic benefits WTE technology environmental sustainability can be summarized as:

- Soil protection: eliminating MSW from landfill
- Air protection: reduction of CH_4 and CO_2
- Water protection: eliminating chemicals from MSW to land and water

The focus of this study was on MSW as fuel for heating and cooling of buildings in the UI Moscow campus. All environmental and financial conclusions are only based on the fuel consumption. For a comprehensive study, the cost of the burner by considering different options ought to be done. Though, the future study would be sizing the burner of MSW for the UI, which is compatible with woodchip burner.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

With the aim of improving sustainability of the district energy plant in the UI Moscow campus, the presented study was planned and conducted. First, to document the history of the boilers in the UI energy plant, the generational differences in technology for each boiler in the last century were mapped in Chapter 2. Then, the four currently operating boilers in the energy plant, each with different equipment configurations, were described, followed by the calculation of energy and exergy efficiency for each. The energy efficiency for each boiler in the district energy plant is from 76% to 85%, while the exergy efficiency for each is from 24% to 27%. The analysis of the emissions products from the biomass and natural gas boilers, shown in Figures 2.7-2.9, was performed to determine the direct impact of each fuel on GHG emissions. The results showed that the moisture content of the biomass (wood chips) has an impact on the CO_2 released during combustion. By decreasing the moisture content in the wood chips, CO_2 emissions were increased. This however had a significant impact on the heating value of the wood chip fuel and more fuel was required to meet the same heating load requirements. This suggests a tradeoff between emissions control and fuel consumption from the amount of moisture in the fuel in the biomass boiler. The natural gas boilers released less CO_2 by volume than the biomass boiler, however unlike biomass, natural gas adds extra CO_2 to the atmosphere. Furthermore, using biomass for heating and cooling at the UI provides a substantial economic benefit compared to natural gas despite its lower heating value, with annual savings of over $1 million.

The next study, Chapter 3, was an investigation based on the exergy analysis of the steam cycle in the UI district energy plant with the purpose of identifying the sources of highest exergy destruction. This data was then used for prioritizing which equipment needed more consideration in the next study. Exergy accounting provides a means to assess the environmental impacts of a system. Through the methods outlined in the chapter, the major exergy destruction rates in the biomass boiler steam cycle are as follows:

- 35% from the biomass boiler
- 33% from the biomass furnace

- 6% from campus heating equipment and steam distribution network
- 3.5% from the PRV

This demonstrated which components in the steam cycle would benefit from enhancement the most. Prioritization should be given to these components to improve the environmental sustainability of the UI energy plant. Parametric studies, shown in Figures 3.5 and 3.6, show that increasing boiler steam pressure results in an increase in exergy efficiency of the boiler. Overall system efficiency did not increase with an increase in boiler steam pressure however. Since exergy destruction in the PRV increased with a higher boiler steam pressure, the PRV was limiting efforts to improve the exergy efficiency of the energy plant.

Modification of the steam plant to eliminate the PRV, through the installation of a single stage, backpressure steam turbine as the primary means of regulating steam pressure was studied in Chapter 4. The study was conducted by defining eight scenarios, outlined here as:

- July Baseline
- Case Study 1 – July model with turbine
- Case Study 2 – July model with turbine at increased pressure
- Case Study 3 – July model with turbine and double effect absorption chiller
- Case Study 4 – July model with turbine, double effect absorption chiller, and increased pressure
- December Baseline
- Case Study 5 – December model with turbine
- Case Study 6 – December model with turbine at increased pressure

After conducting the thermodynamic analysis, simulation, and modeling with TRNSYS software the above scenarios resulted in similar outcomes. A turbine could increase system energy and exergy efficiency while providing economic benefits. Improvements in system energy efficiency are summarized as the following:

- 3-4% increase by adding a steam turbine and increasing boiler steam pressure
- 17% further increase by adding the double effect absorption chiller

Improvements in system exergy efficiency are summarized as:

- 4-5% increase by adding a steam turbine and increasing boiler steam pressure
- 2% further increase by adding the double effect absorption chiller

The potential economic savings were greatest when boiler steam pressure was increased, shown in Figure 4.5, as more power was produced from the turbine. The study showed that the efficient use of energy resources, through proper operating conditions and equipment selection, could be beneficial economically and for long-term sustainability. Using heat to produce work, in this case by operating a steam driven turbine instead of a PRV, was more sustainable than the current configuration because of reduced exergy destruction. In contrast, increasing cooling capacity by operating a double effect absorption chiller, while resulting in a significant increase in energy efficiency, was less sustainable. This was due to the reduced exergy content of the heat energy compared to electricity. Financial benefits were results of reducing the campus electricity demand or by selling the electricity back to the utility.

Greenhouse emissions are an ever-increasing concern in today's world. Using energy resources more efficiently has the twofold effect of reducing fuel costs and net GHG emissions to the environment. Further environmental improvements were studied in Chapter 5 by considering MSW as a fuel in addition to the current wood chip and natural gas at UI energy plant. The feasibility study of implementing WTE technology at the UI Moscow campus was conducted by estimating the total volume and heating values of MSW available in the local community. In this study three different scenarios, shown in Figure 5.4, were defined as follows:

- Current fuel mixture
- UI Moscow campus MSW
- Surrounding area

It was found that the MSW generated on campus could meet 2% of the steam production requirements, while the surrounding area could meet 42%. The results in Table 5.8 showed that GHG emissions were greater when combusting biomass compared to natural gas, however biomass did not contribute to total atmospheric CO_2 levels, and consequently to global warming. Fuel types such as biomass are carbon neutral, however they impact the environment nonetheless. Considering MSW as fuel in the UI energy plant was an effective means of addressing the environmental impacts of landfills while producing energy. WTE technology, in addition to protection of the soil and ground water, resulted in fewer CH_4 emissions, which damage the environment far more than CO_2.

6.2 Recommendations for the UI energy plant

The district energy system has been an effective way for the UI to meet the heating and cooling demands of the Moscow campus. There are opportunities in the UI district energy plant to reduce environmental impacts for advancing sustainability. The boiler steam pressure has been kept low to reduce pumping costs. It is suggested that boiler steam pressure be adjusted to higher pressure levels which reduces exergy destruction in the boiler in addition to improving the potential performance of a steam turbine. This can increase the exergy efficiency of the UI district energy plant from 4% to 7%. The higher pumping costs associated with the increased boiler steam pressure will be offset by the substantial economic benefits provided by generated electricity through the turbine. A small turbine (250-500 kW) capable of meeting operations in the energy plant would be more efficient than a larger one, since it would be running at peak efficiency even when steam production is low. An assessment on the initial investment, sizing, and installation of the turbine should be conducted in the future.

District energy meets energy demands in ways beyond efficient equipment configurations. The ability to use different energy resources in district energy systems is advantageous. Its flexibility allows for the use of multiple energy resources together, where a single resource might be insufficient. Since the handling of biomass and MSW is similar when being incinerated, combining the two fuels to meet future the UI heating and cooling demand is suggested.

6.3 Potential Future Research

It was identified during the research that the moisture content in the biomass fuel used at UI energy plant has a significant impact on the fuel consumption and CO_2 emissions of the biomass boiler. Both moisture content and fuel consumption vary at the plant. Moisture is measured and recorded occasionally throughout the day, but this data is not used to control boiler operations. Fuel consumption is only measured at the end of each day in terms of loads delivered via trucks. It is suggested that real time data collection of both moisture content and fuel consumption be implemented for the biomass boiler. That can be used to develop an objective function for optimizing boiler efficiency as a function of moisture content, cost, and CO_2 emissions of the wood chips as well as the ambient temperature.

Increasing performance and sustainability based on the campus building loads can be investigated for the UI district heating and cooling network. In this study, the campus energy load was modeled as a heat exchanger due to its complexity. While this is sufficient to model the energy plant, there are likely substantial benefits to be had by improvements within the campus itself. Unfortunately, modeling over sixty individual buildings connected to the heating network would be a vast study in itself. Modeling the steam network and the heating/cooling equipment in the buildings is suggested as a future study.

References

[1] I. Dincer, “Renewable energy and sustainable development: a crucial review,” *Renew. Sustain. Energy Rev.*, vol. 4, no. 2, pp. 157–175, 2000.

[2] M. Kanoglu, I. Dincer, and M. A. Rosen, “Understanding energy and exergy efficiencies for improved energy management in power plants,” *Energy Policy*, vol. 35, no. 7, pp. 3967–3978, 2007.

[3] I. Dincer, “The role of exergy in energy policy making,” *Energy Policy*, vol. 30, no. 2, pp. 137–149, 2002.

[4] S. Kahn Ribeiro, S. Kobayashi, M. Beuthe, J. Gasca, D. Greene, D. S. Lee, Y. Muromachi, P. J. Newton, S. Plotkin, D. Sperling, R. Wit, and P. J. Zhou, “Transport and its infrastructure,” *Clim. Chang. 2007 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fourth Assess. Rep. Intergov. Panel Clim. Chang.*, 2007.

[5] P. Regulagadda, I. Dincer, and G. F. Naterer, “Exergy analysis of a thermal power plant with measured boiler and turbine losses,” *Appl. Therm. Eng.*, vol. 30, no. 8–9, 2010.

[6] United States Environmental Protection Agency, “Inventory of U.S. greenhouse gas emissions and sinks: 1990-2013,” Washington DC, USA, 2016.

[7] Climate Protection Partnership Division, “Greenhouse Gas Inventory Offset Project Methodology for Project Type: Industrial Boiler Efficiency,” *United States Environ. Prot. Agency*, no. August, 2008.

[8] United States Energy Information Administration, “Monthly Energy Review, January 2016,” Washington DC, USA, 2016.

[9] L. Zhang, C. Xu, and P. Champagne, “Overview of recent advances in thermo-chemical conversion of biomass,” *Energy Convers. Manag.*, vol. 51, no. 5, 2010.

[10] G. Qiu, “Testing of flue gas emissions of a biomass pellet boiler and abatement of particle emissions,” *Renew. Energy*, vol. 50, pp. 94–102, 2013.

[11] B. Rezaie and M. A. Rosen, “District heating and cooling: Review of technology and potential enhancements,” *Appl. Energy*, vol. 93, pp. 2–10, 2012.

[12] J. S. Nijjar, A. S. Fung, L. Hughes, and H. Taherian, “District heating system design for rural Nova Scotian communities using building simulation and energy usage databases,” *Trans. Can. Soc. Mech. Eng.*, vol. 33, no. 1, pp. 51–63, 2009.

[13] A. Lake, B. Rezaie, and S. Beyerlein, “Review of district heating and cooling systems for a sustainable future,” *Renew. Sustain. Energy Rev.*, vol. 67, pp. 417–425, 2017.

[14] B. Rezaie, B. V. Reddy, and M. A. Rosen, “An enviro-economic function for assessing energy resources for district energy systems,” *Energy*, vol. 70, pp. 159–164, 2014.

[15] B. Rezaie, B. V. Rezaie, and M. A. Rosen, “Economic and CO2 emissions comparison of district energy systems using geothermal and solar energy resources,” in *3rd World Sustainability Forum*, 2013.

[16] M. A. Rosen, M. N. Le, and I. Dincer, “Efficiency analysis of a cogeneration and district energy system,” *Appl. Therm. Eng.*, vol. 25, no. 1, pp. 147–159, 2005.

[17] United States Department of Energy, “Biomass Energy Data Book,” vol. 4, pp. 9, 201, 2011.

[18] A. Demirbas, “Combustion characteristics of different biomass fuels,” *Prog. Energy Combust. Sci.*, vol. 30, no. 2, pp. 219–230, 2004.

[19] Z. T. Lian, K. J. Chua, and S. K. Chou, “A thermoeconomic analysis of biomass energy for trigeneration,” *Appl. Energy*, vol. 87, no. 1, pp. 84–95, 2010.

[20] P. Basu, J. Butler, and M. A. Leon, “Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants,” *Renew. Energy*, vol. 36, no. 1, pp. 282–288, 2011.

[21] C. Martín, M. A. Villamañán, C. R. Chamorro, J. Otero, A. Cabanillas, and J. J. Segovia, “Low-grade coal and biomass co-combustion on fluidized bed: Exergy analysis,” *Energy*, vol. 31, no. 2–3, pp. 330–344, 2006.

[22] R. U. Ayres, L. Ayres, and K. Martinas, “Eco-thermodynamics: exergy and life cycle analysis,” *Insead*, pp. 1–22, 1996.

[23] Energy and Environmtental Analysis Inc., “Characterization of the U.S. industrial/commercial boiler population,” 2005.

[24] S. Klein and G. Nellis, *Thermodynamics*. New York: Cambridge University Press, 2012.

[25] A. Franco and N. Giannini, “Perspectives for the use of biomass as fuel in combined cycle power plants,” *Int. J. Therm. Sci.*, vol. 44, no. 2, pp. 163–177, 2005.

[26] R. Saidur, E. A. Abdelaziz, A. Demirbas, M. S. Hossain, and S. Mekhilef, “A review on biomass as a fuel for boilers,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2262–2289, 2011.

[27] P. Quaak, H. Knoef, and H. Stassen, “Energy from biomass: A review of combustion and gasification technologies,” *World Bank Tech. Pap.*, no. 422, p. 4, 1999.

[28] P. L. Wilson, J. W. Funck, and R. B. Avery, “Fuelwood Characteristics of Northwestern Conifers and Hardwoods (Updated),” no. April, p. 58, 2010.

[29] S. V. Vassilev, D. Baxter, L. K. Andersen, and C. G. Vassileva, “An overview of the chemical composition of biomass,” *Fuel*, vol. 89, no. 5, pp. 913–933, 2010.

[30] R. Saidur, J. U. Ahamed, and H. H. Masjuki, “Energy, exergy and economic analysis of industrial boilers,” *Energy Policy*, vol. 38, no. 5, pp. 2188–2197, 2010.

[31] M. Kanoglu, I. Dincer, and M. A. Rosen, “Understanding energy and exergy efficiencies for improved energy management in power plants,” *Energy Policy*, vol. 35, no. 7, 2007.

[32] T. Klason, *Modelling of Biomass Combustion in Furnaces*, no. May. 2006.

[33] “Protection of the Environment, 40 CFR pt. 60, 2016.” .

[34] M. A. Rosen, “Energy sustainability: A pragmatic approach and illustrations,” *Sustainability*, vol. 1, no. 1, pp. 55–80, 2009.

[35] T. E. Graedel and B. R. Allenby, *Industrial Ecology and Sustainable Engineering*. Upper Saddle River, NJ: Prentice Hall, 2010.

[36] M. A. Rosen, “Assessing energy technologies and environmental impacts with the principles of thermodynamics,” *Appl. Energy*, vol. 72, no. 1, pp. 427–441, 2002.

[37] U. S. Environmental Protection Agency, “Inventory of U.S. greenhouse gas emissions and sinks : 1990–2014,” Washington DC, USA, 2016.

[38] A. Omer, “Energy, environment and sustainable development,” *Renew. Sustain. Energy Rev.*, vol. 12, no. 9, pp. 2265–2300, 2008.

[39] W. Gang, S. Wang, F. Xiao, and D. C. Gao, “District cooling systems: Technology integration, system optimization, challenges and opportunities for applications,” *Renew. Sustain. Energy Rev.*, vol. 53, pp. 253–264, 2016.

[40] M. Gong and S. Werner, “Exergy analysis of network temperature levels in Swedish and Danish district heating systems,” *Renew. Energy*, vol. 84, pp. 106–113, 2015.

[41] M. Gong and S. Werner, “Mapping energy and exergy flows of district heating in Sweden,” in *The 15th International Symposium on District Heating and Cooling*, 2016.

[42] J. Szargut, D. R. Morris, and F. R. Steward, *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*. Hemisphere Publishing Corporation, 1988.

[43] E. Sciubba and G. Wall, “A brief commented history of exergy from the beginnings to 2004,” *Int. J. Thermodyn.*, vol. 10, no. 1, pp. 1–26, 2007.

[44] E. Sciubba, “Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems,” *Exergy, An Int. J.*, vol. 1, no. 2, pp. 68–84, 2001.

[45] R. U. Ayres, L. W. Ayres, and K. Martinas, “Eco-thermodynamics: Exergy and life cycle analysis,” Fontainebleau, France, 1996.

[46] M. A. Rosen and I. Dincer, “Exergy as the confluence of energy, environment and sustainable development,” *Exergy, An Int. J.*, vol. 1, no. 1, pp. 3–13, 2001.

[47] I. Dincer and M. A. Rosen, “A worldwide perspective on energy, environment and sustainable development,” *Int. J. Energy Res.*, vol. 22, no. 15, pp. 1305–1321, 1998.

[48] I. Dincer and M. A. Rosen, “Energy, environment and sustainable development,” *Appl. Energy*, vol. 64, pp. 427–440, 1999.

[49] I. Dincer and M. A. Rosen, “Thermodynamic aspects of renewables and sustainable development,” *Renew. Sustain. Energy Rev.*, vol. 9, no. 2, pp. 169–189, 2005.

[50] H. Caliskan, “Thermodynamic and environmental analyses of biomass, solar and electrical energy options based building heating applications,” *Renew. Sustain. Energy Rev.*, vol. 43, pp. 1016–1034, 2015.

[51] A. Lake and B. Rezaie, “Use of Exergy Analysis to Quantify the Effect of Lithium Bromide Concentration in an Absorption Chiller,” *Entropy*, vol. 19, no. 4, p. 156, 2017.

[52] M. Compton and B. Rezaie, “Enviro-exergy sustainability analysis of boiler evolution in district energy system,” *Energy*, vol. 119, pp. 257–265, 2017.

[53] M. Terhan and K. Comakli, “Energy and exergy analyses of natural gas-fired boilers in a district heating system,” *Appl. Therm. Eng.*, vol. 121, pp. 380–387, 2017.

[54] M. Gürtürk and H. F. Oztop, “Exergy analysis of a circulating fluidized bed boiler cogeneration power plant,” *Energy Convers. Manag.*, vol. 120, pp. 346–357, 2016.

[55] J. A. M. Silva, S. Ávila, and M. Carvalho, “Assessment of energy and exergy efficiencies in steam generators,” *J. Brazilian Soc. Mech. Sci. Eng.*, 2017.

[56] S. Adibhatla and S. C. Kaushik, “Exergy and thermoeconomic analyses of 500 MWe sub critical thermal power plant with solar aided feed water heating,” *Appl. Therm. Eng.*, vol. 123, pp. 340–352, 2017.

[57] R. U. Ayres, L. W. Ayres, and K. Martinas, “Exergy, waste accounting, and life-cycle analysis,” *Energy*, vol. 23, no. 5, pp. 355–363, 1998.

[58] J. Dewulf, M. E. Boesch, B. De Meester, G. Van Der Vorst, H. Van Langenhove, S. Hellweg, and M. A. J. Huijbregts, "Supporting information: Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting," *Environ. Sci. Technol.*, vol. 41, pp. 8477–8483, 2007.

[59] R. L. Cornelissen and G. G. Hirs, "The value of the exergetic life cycle assessment besides the LCA," *Energy Convers. Manag.*, vol. 43, no. 9–12, pp. 1417–1424, 2002.

[60] E. Guelpa, C. Toro, A. Sciacovelli, R. Melli, E. Sciubba, and V. Verda, "Optimal operation of large district heating networks through fast fluid-dynamic simulation," *Energy*, vol. 102, pp. 586–595, 2016.

[61] R. A. Gaggioli, "The dead state," *Int. J. Thermodyn.*, vol. 15, no. 4, pp. 191–199, 2012.

[62] E. Sciubba, S. Bastianoni, and E. Tiezzi, "Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy," *J. Environ. Manage.*, vol. 86, no. 2, pp. 372–382, 2008.

[63] P. L. Wilson, J. W. Funck, and R. B. Avery, "Fuelwood characteristics of northwestern conifers and hardwoods (updated)," Portland, Oregon, USA, 2010.

[64] S. Sengupta, A. Datta, and S. Duttagupta, "Exergy analysis of a coal-based 210MW thermal power plant," *Int. J. Energy Res.*, vol. 31, pp. 14–38, 2007.

[65] M. Szega and P. Żymelka, "Thermodynamic and economic analysis of the production of electricity, heat and cold in the CHP unit with the absorption chillers," *J. Energy Resour. Technol.*, no. c, pp. 1–28, 2017.

[66] G. Pagliarini, C. Corradi, and S. Rainieri, "Hospital CHCP system optimization assisted by TRNSYS building energy simulation tool," *Appl. Therm. Eng.*, vol. 44, pp. 150–158, 2012.

[67] F. Drake, "Evaluating Cogeneration Options for a Campus Heating and Cooling Plant," Madison, Wisconsin, USA, 1988.

[68] M. D. Schicktanz, J. Wapler, and H. Henning, “Primary energy and economic analysis of combined heating, cooling and power systems,” *Energy*, vol. 36, no. 1, pp. 575–585, 2011.

[69] M. A. Rosen, I. Dincer, and M. Kanoglu, “Role of exergy in increasing efficiency and sustainability and reducing environmental impact,” *Energy Policy*, vol. 36, no. 1, pp. 128–137, 2008.

[70] A. Kallert, D. Schmidt, and T. Bläse, “Exergy-based analysis of renewable multi-generation units for small scale low temperature district heating supply,” *Energy Procedia*, vol. 116, pp. 13–25, 2017.

[71] S. Adibhatla and S. C. Kaushik, “Energy, exergy, economic and environmental (4E) analyses of a conceptual solar aided coal fired 500 MWe thermal power plant with thermal energy storage option,” *Sustain. Energy Technol. Assessments*, vol. 21, pp. 89–99, 2017.

[72] A. Alam, M. A. Siddiqui, and N. ur Rehman, “Solar feed water heating feasibility for a conventional steam power plant,” *J. Mech. Sci. Technol.*, vol. 31, no. 7, pp. 3573–3580, 2017.

[73] P. Gonçalves, G. Angrisani, C. Roselli, A. R. Gaspar, and M. G. Silva, “Energy and Exergy-based modeling and evaluation of a micro-combined heat and power unit for residential applications,” in *MicrogenIII: Proc of the 3rd ed of the int conf on microgeneration and related tech*, 2013.

[74] S. Klein, “TRNSYS 17: A Transient System Simulation Program.” University of Wisconsin, Madison, USA, 2010.

[75] United States Environmental Protection Agency, “Advancing sustainable materials management: 2014 fact sheet,” Washington DC, USA, 2016.

[76] T. Michaels and I. Shiang, “2016 Directory of waste-to-energy facilities,” *Energy Recover. Counc.*, pp. 1–72, 2016.

[77] N. Themelis, “Waste-to-energy : Renewable energy instead of greenhouse gas emissions,” *Earth Eng. Center, Columbia Univ. New York, USA*, 2007.

[78] L. Lombardi, E. Carnevale, and A. Corti, "A review of technologies and performances of thermal treatment systems for energy recovery from waste," *Waste Manag.*, vol. 37, pp. 26–44, 2015.

[79] C. Ryu and D. Shin, "Combined heat and power from municipal solid waste: Current status and issues in South Korea," *Energies*, vol. 6, no. 1, pp. 45–57, 2013.

[80] M. Pavlas, M. Touš, P. Klimek, and L. Bébar, "Waste incineration with production of clean and reliable energy," *Clean Technol. Environ. Policy*, vol. 13, no. 4, pp. 595–605, 2011.

[81] T. Fruergaard, T. H. Christensen, and T. Astrup, "Energy recovery from waste incineration: Assessing the importance of district heating networks," *Waste Manag.*, vol. 30, no. 7, pp. 1264–1272, 2010.

[82] T. Nagawiecki, "University of Idaho waste characterization," Moscow, Idaho, USA, 2009.

[83] B. Staley and M. Barlaz, "Composition of municipal solid waste in the United States and implications for carbon sequestration and methane yield," *J. Environ. Eng.*, vol. 135, no. 10, pp. 901–909, 2009.

[84] United States Energy Information Administration, "Methodology for allocating municipal solid waste to biogenic and non-biogenic energy," Washington DC, USA, 2007.

[85] N. J. Themelis and C. Mussche, "2014 energy and economic value of municipal solid waste (MSW), Including non-recycled plastics (NRP), currently landfilled in the fifty states," *Columbia Univ.*, p. 40, 2014.

[86] Franklin Associates, "Cradle-to-gate life cycle inventory of nine plastic resins and four polyurethane precursors," Prairie Village, Kansas, USA, 2011.

[87] D. Tsiamis and M. Castaldi, "Determining accurate heating values of non-recycled plastics (NRP)," *City Univ. New York*, pp. 1–27, 2016.

[88] United States Environmental Protection Agency, “Documentation of emission estimation methodologies for sources of 112(c)(6) pollutants: Appendix A,” Washington DC, USA, 1998.

[89] B. Boundy, S. W. . Diegel, L. Wright, and S. C. Davis, *Biomass Energy Data Book*, vol. 4. U.S. Department of Energy, 2011.

[90] P. H. Brunner and H. Rechberger, “Waste to energy - key element for sustainable waste management,” *Waste Manag.*, vol. 37, pp. 3–12, 2015.

[91] FCS Group, “City of Moscow sanitation, water, and wastewater rate study,” Moscow, Idaho, USA, 2013.

[92] T. Michaels, “2014 ERC directory of waste-to-energy facilities,” *Energy Recover. Counc.*, pp. 1–72, 2014.

[93] United States Census Bureau, “QuickFacts: Latah county, Idaho, United States,” 2016. [Online]. Available: https://www.census.gov/quickfacts/fact/table/latahcountyidaho,US/PST045216. [Accessed: 29-Mar-2017].

[94] N. Deshais, “Talking trash,” *Washington State Magazine*, Pullman, Washington, USA, Aug-2014.

[95] N. Themelis and P. Ulloa, “Methane generation in landfills,” *Renew. Energy*, vol. 32, no. 7, pp. 1243–1257, 2007.

[96] L. O’Rourke, K. Read, and E. Johnston, “U.S. Freight GHG Emissions by Consuming Industry Segment,” Fairfax, Virginia, USA, 2015.

[97] United States Energy Information Administration, “Carbon dioxide emissions coefficients,” 2016. [Online]. Available: https://www.eia.gov/environment/emissions/co2_vol_mass.php.

Appendix 1

Chapter 2: Copyright Approval from *Energy*

Copyright Clearance Center RightsLink®

Home | Create Account | Help

Title: Enviro-exergy sustainability analysis of boiler evolution in district energy system

Author: M. Compton,Behnaz Rezaie

Publication: Energy

Publisher: Elsevier

Date: 15 January 2017

LOGIN

If you're a copyright.com user, you can login to RightsLink using your copyright.com credentials. Already **a RightsLink user** or want to learn more?

Please note that, as the author of this Elsevier article, you retain the right to include it in a thesis or dissertation, provided it is not published commercially. Permission is not required, but please ensure that you reference the journal as the original source. For more information on this and on your other retained rights, please visit: https://www.elsevier.com/about/our-business/policies/copyright#Author-rights

BACK | CLOSE WINDOW

Appendix 2

Chapter 3: Copyright Approval from *The International Journal of Exergy*

From: Jeanette Brooks <jrb@inderscience.com>

Today, 2:46 AM

Thank you Marc for your email – yes we give you permission to include your work as mentioned below in your Master's thesis. Please ensure full acknowledgement of the original source of publication is made clear, and include a statement that Inderscience retains copyright of the article.

Kind regards

Jeanette

J R Brooks (Dr)

Publications Director

Email: jrb@inderscience.com

Inderscience Enterprises Limited

World Trade Centre Building II

29 route de Pre-Bois

Case Postale 856

CH-1215 Geneve 15

Switzerland

From: Compton, Marc (comp8033@vandals.uidaho.edu)

To: copyright@inderscience.com; Rezaie, Behnaz (rezaie@uidaho.edu)

Inderscience,

I would like to request copyright permission to use my work titled "Exergy Approach for Advancing Sustainability of a Biomass Boiler" in my Master's thesis at the University of Idaho. The authors are Marc Compton, Dr. Behnaz Rezaie, and Dr. Marc Rosen. The article has been accepted for publication and is currently in production. The DOI number is not yet available.

Thanks,

Marc Compton

Appendix 3

Chapter 4: Supplemental Information for Developing the TRNSYS Model

A3.1 Introduction

This appendix provides additional information on the TRNSYS model developed in Chapter 4. This includes descriptions of components figures not present.

It is strongly recommended that the user have prior knowledge of the TRNSYS user interface. It is not the intention of this appendix to teach the user how to use and navigate TRNSYS, rather this appendix is designed to familiarize the user with the TRNSYS model developed in Chapter 4 of this thesis. Training videos have been recorded for users new to TRNSYS. For access to these videos an inquiry should be sent to Dr. Behnaz Rezaie at the University of Idaho.

A3.2 Additional Components

There are many supplementary components in the model, listed below in Table A3.1, that are not described in Chapter 4. The reason for this is that the additional components might require little input from the user beyond connecting them to the main components, or they might be used to provide data and feedback to the user. For example, Type 65d outputs system variables as the simulation is running and has no interaction with the simulation itself. It is merely designed to provide visual feedback to the user to be interpreted as needed, generally for troubleshooting purposes.

A3.3 TRNSYS Model

The full layout of the TRNSYS model is shown below. Figure A3.1 shows the model for case studies 1 and 2, where the single effect absorption chiller and steam turbine are present. Figure A3.2 shows the model for case studies 3 and 4, with the single and double effect absorption chillers and the steam turbine. Figure A3.3 shows the model for case studies 5 and 6 in the winter, when only the steam turbine is present. The additional components that are listed in Table A3.1 are visible, along with every connection needed in then model.

Table A3.1. Description of additional system components in the TRNSYS model [74].

Equations:	Equations in TRNSYS do not have a specific type. Instead they are added directly to the model. They are represented in the graphical interface with the image of a calculator. They allow the user to define equations within the input file which are not in an individual component. These equations can then be used as inputs for other components.
Type 9e:	Type 9e reads data at regular time intervals from a separate data file, converting it into a desired system of units, and making the data available to other components as time varying forcing functions. The data line to line must be at constant time intervals.
Type 15:	Type 15-TMY3 reads data at regular time intervals from an external weather data file, in this case TMY3, and makes that data available to other components in the system. Some key variables include solar radiation, mains water temperature, effective sky temperature, percent relative humidity, etc. Since an exergy analysis requires ambient conditions at the dead state to be known, this component also allows for exergy calculations to be run. Weather data is gathered from Coeur d'Alene, Idaho.
Type 25c:	Type 25c is used to output (or print) selected system variables at specified time intervals. Units (such as kJ/hr, kW, temperature, etc.) are not printed with the output file. Each time the simulation is run, the output file is generated. This output file can then be used in external programs as desired.
Type 65d:	Type 65d is used to display selected system variables while the simulation is running. The component is widely used since it provides valuable variable information and allows the user to see system performance. This is very useful for troubleshooting purposes. Selected variables are displayed in a separate plot window. Using multiple Type 65d components allows for variables to be plotted separately when appropriate (plotting all mass flows together in one window for example, while having power consumption in another). The component does not output any data file.
Type 595:	Type 595 models a simple mixing valve which can have up to 100 separate inlet ports. Outlet properties are set by an overall energy balance of the inlet flow streams. The outlet flow rate returns the sum of the inlet flow rates.
Type 647:	Type 647 models a diverting valve that splits an inlet mass flow into fractional outlet mass flows. The inlet flow may be split up to 100 individual times.

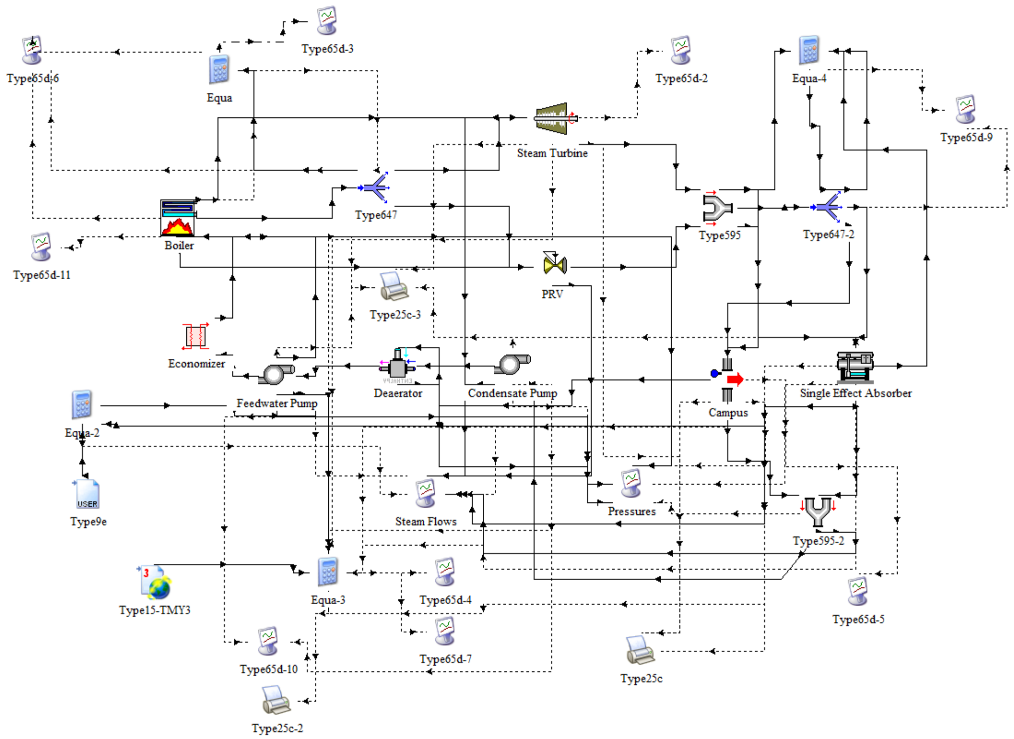

Figure A3.1. Full graphical representation of TRNSYS model for case studies 1 and 2.

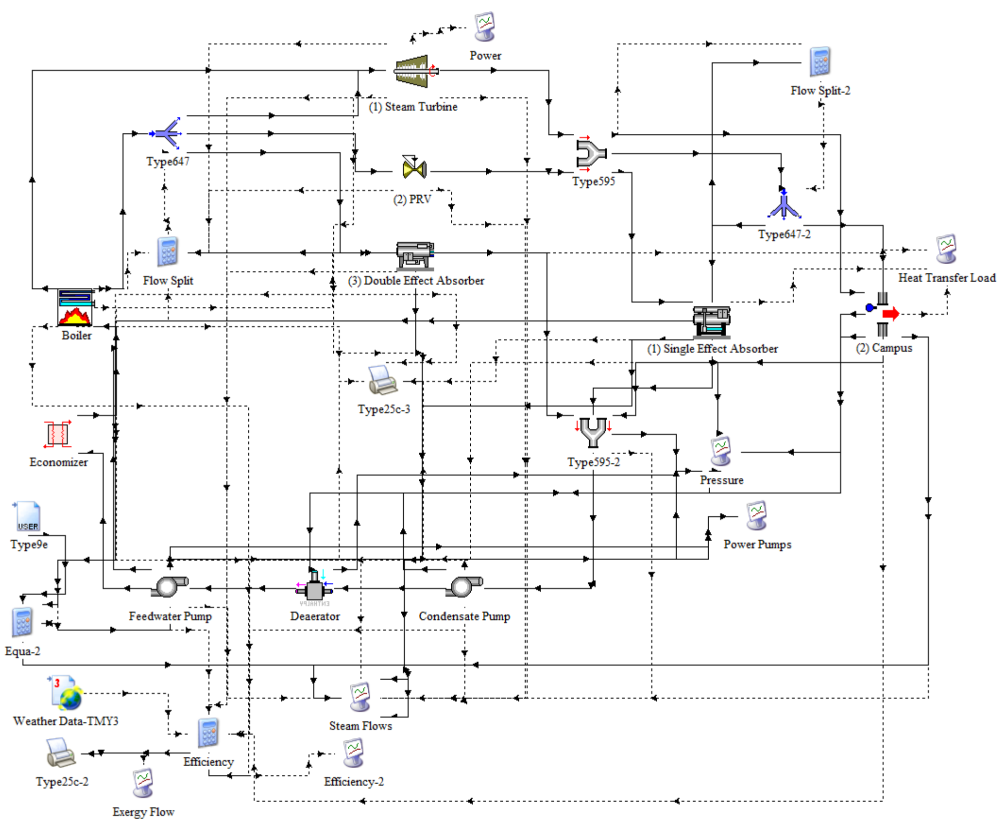

Figure A3.2. Full graphical representation of TRNSYS model for case studies 3 and 4.

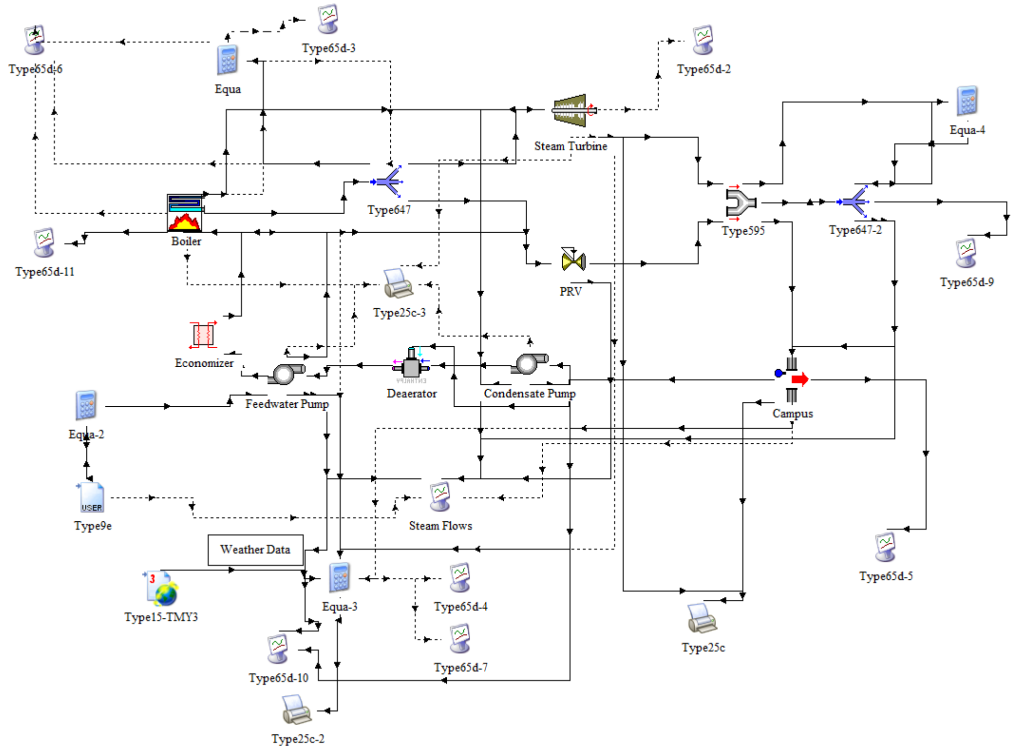

Figure A3.3. Full graphical representation of TRNSYS model for case studies 5 and 6.