Energy and Exergy Assessment of the Absorption Chiller and Cold Thermal Energy Storage in District Cooling

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Authorization to Submit Thesis

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Abstract

A comprehensive review of the advantages and disadvantages of energy sources, global policies and current research in district energy systems was conducted. Then thermodynamic analysis was applied to the University of Idaho's chilled water system, with a focus on the absorption chiller and the thermal energy storage tank. By calculating and modeling the system, exergy destruction rates and efficiencies were quantified. Suggestions for improvement to these systems were presented based upon the models created and validated during these studies. Improvements to the absorption chiller were available by optimizing the solution concentration levels. Minor adjustments can yield a decrease in the overall exergy destruction rates within the chiller. The thermal energy storage study showed a decrease in exergy efficiency throughout the charging process. This indicated that fully charging the storage tank resulted in lower overall efficiency of the system. Small changes in the operation of chilled water equipment can improve their sustainable aspects.

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List of Nomenclature

DE District energy

GHGs Greenhouse gasses

TES Thermal energy storage

UI University of Idaho

A Cross sectional area (m^2)

α Thermal Diffusivity (m^2/s)

β Volumetric coefficient of thermal expansion (1/K)

Bi Biot Number

C Specific heat of a fluid (kJ/kg-K)

D_i Diameter of tank

Δ Delta, difference between initial and final values

δ Wall thickness

E Thermal capacity

E_{max} Maximum thermal capacity

Ƞ Efficiency

Fo Fourier Number

g Gravity

Gr Grashof Number

h Specific enthalpy (kJ/kg)

H Height of the tank (m)

h_o Convective value (W/m^2-K)

k Conductivity (W/m-K)

kw Conductivity of the wall (W/m-K)

L Length (m)

$\dot{m}$ Mass flow rate (kg/s)

μ Viscosity (kg/m-s)

P Pressure (kPa)

Pe Peclet Number

Pr Prandtl Number

Ψ Specific exergy (kJ/kg)

$\dot{Q}$ Heat transfer rate (kW)

ρ Density

Re Reynolds Number

Ri Richardson Number

s Specific entropy (kJ/kg-K)

SHX Solution Heat Exchanger

T Temperature (º C or K)

t time (s)

T_{max} Maximum return temperature (º C or K)

TES Thermal Energy Storage

V Velocity (m/s)

$X^{\cdot}$ Exergy rate (KJ/kg)

Z Height (m)

η Efficiency

Subscripts

0 Reference Property

b Boundary

C Charging

cw Chilled water

D Discharging

en Energy

f Flow

int Internal

Q Heat transfer

sys System

w Work

x Exergy

Chemical Symbols

CO_2 Carbon dioxide

Chapter 1: Introduction

1.1 Motivation

Demand for energy is inevitable for the future of society. Reducing the current energy usage can be done by creating new equipment or improving old and existing systems. New and existing technologies should both be evaluated on their environmental impacts as well as their efficient and responsible use of energy sources. Understanding these systems, discussing alternatives to improve efficiency and reducing environmental impacts should always be a part of the development and operation cycles.

The goal of energy efficiency should not be perused without first consideration of the environmental impacts of that decision. The environmental impacts should also not be considered without also addressing the energy efficiency changes that would result. There is a balance, optimal or ideal level that should always be considered before developing new technologies. There are many approaches to solve this problem; one such approach is district energy (DE) systems.

DE systems offer opportunities to provide a heating, cooling, and electricity to industrial parks and residential buildings. Using thermal networks to transmit energy, DE systems offer greater efficiencies than traditional systems for heating and cooling. DE systems are capable of utilizing fossil fuels (coal, oil and natural gas), biomass, and solar to generate the heating, cooling and electricity.

The main motivation of the thesis is to improve energy efficiency by discussing the current equipment and practices used in the case studies presented. By applying the energy and exergy assessment of an absorption chiller and cold thermal energy storage (TES) in district cooling presented a suitable tool can be developed for similar systems with the goal of improving efficiency.

1.2 Objectives and Scope

This thesis focuses on equipment located at the energy plant located at the University of Idaho campus in Moscow, Idaho, USA. The DE system primarily operates a biomass boiler which produces steam used for heating and laboratory processes on campus.

Throughout the year, the energy plant also employs the use of a condensing absorption chiller and thermal energy storage tank.

The path of this thesis is presented to show the methodology to achieve the objectives.

1. Develop a comprehensive model of the equipment using energy and exergy equations.
2. Analyze data obtained from both measuring instruments as well as the models created.
3. Check validity of the models, and compare results to other studies presented on similar topics.
4. Provide recommendations for improvement of the current system to increase efficiency.

The scope of this research is to study the TES and a condensing absorption chiller and offer an investigation in to the operation and efficiencies of the equipment during typical use. The goal is to assist designers, researchers, future engineers and managers by providing insight into practical methods to enhance performance of select equipment used in district cooling systems.

1.3 Outline

District energy systems have been around since the 14th century [1]. Since then these systems have gone through a number of changes in energy sources including geothermal, biomass, and fossil fuels. These systems utilize piping and ducts to move a working fluid to transport this energy. Early systems were contained within apartment style buildings to distance people from the risk of steam boiler explosions. As technology and transport methods improved lower temperatures and pressures were used, longer distances traveled, and prefabricated systems were developed.

Many studies have shown that district energy systems have a higher efficiency when compared to individual heating and cooling. Current limiting factors on the sustainable aspects of these systems are rooted in environmental impacts, economic feasibility, and energy polices of local, national, and global governing bodies. Decisions on performance criteria should align with sustainable fuel sources to produce clean sources of heating and cooling to residential and commercial buildings in an environmentally safe and responsible manner.

District energy plants can produce any or all of the following: hot water, steam, chilled water and electricity. Currently the University of Idaho utilizes an energy plant to provide the campus with most of its heating and cooling needs throughout the year. The current energy plant as of 2017 includes a boiler, three vapor compression chillers, two lithium-bromide condensing absorption chillers and a thermal energy storage tank.

This thesis is comprised of three papers with the goal of focusing on district cooling on the Moscow campus of the University of Idaho. This part of the system utilizes equipment that produces, stores and transports chilled water throughout campus. The first paper (Chapter 2) focuses on a review of the current state of district energy systems, the policies on energy that affect them, and various design considerations that should be addressed before a system is installed.

Utilization of exergy analysis on one of the absorption chillers is discussed in the second paper (Chapter 3). This equipment is constantly in use throughout the year, and offers potential for improvement to the sustainability aspects of the university. The goal of this paper was to use measured data obtained during operation with the purpose of evaluating the exergy efficiency of this chiller. Then using a model, predict changes and adjustments that could be made to the lithium-bromide concentration to increase efficiency of the equipment. By adjusting this concentration internal temperatures are affected; this results in changes in the internal exergy destruction of the chiller.

The third paper (Chapter 4) focuses on the thermal energy storage tank located on campus. This tank is 86 feet tall, and contains 2 million gallons of water. This system is charged during the cool evening and night hours and discharged during the peak hours of the day. The goal of this paper was to address the exergy efficiency of the whole storage tank as well as evaluate the efficiency within internal segments. Data obtained throughout the 2016 cooling season provided a significant opportunity to quantify how to obtain the best efficiency while also maximizing the total available energy storage.

The final chapter (Chapter 5) offers recommendations for improving the systems analyzed in the previous chapters. The goal of these changes is to facilitate discussion on the best way to increase the exergy efficiency of the chilled water system throughout the year. In addition to the alterations to the systems presented, future work is also discussed. The future work discusses topics and areas that were discovered during research; each topic included in this section showed value in additional focus, expanding upon the ideas presented in this study.

Chapter 2: Review of District Heating and Cooling Systems for Sustainable Future

A. Lake, B. Rezaie, and S. Beyerlein, “Review of district heating and cooling systems for a sustainable future”, *Renewable and Sustainable Energy Reviews*, 2017, 67, 417-425

2.1 Abstract

The present study explores the implementation of district heating and cooling systems across a broad set of case studies reported in the literature. Topics addressed include their history, system identification, energy sources, design considerations, environmental impact, economic feasibility, performance analysis and the role of energy policy. The history of district heating and cooling systems reveals how available technology has influenced the configuration of district energy systems as more efficient and cleaner methods of providing heating and cooling have arisen. This leads to system identification based on primary energy sources, including the deployment of more and more renewable energy streams. Advantages and disadvantages of each energy source are examined in detail. Policies created by government and international entities will have a major impact on the future of research and development in district energy systems. Incentives may become necessary for creating favorable conditions for the efficient construction and utilization of district heating and cooling. Outcomes of these policies influence design considerations underlying any district energy system and their sustainability. Studies on greenhouse gas emissions along with the economic impacts of district energy construction are part of the design process and optimization of district energy systems should include economic and environmental considerations and not solely thermal efficiency. District heating and cooling systems are often integrated with components such as absorption chillers, cogeneration and thermal energy storage. Performance analysis using exergy and energy analysis have revealed several sources of irreversibility in district heating systems with these elements. If understood properly, these can greatly enhance system operation. Awareness and accommodation of the many factors discussed in this paper can improve the soundness of any district heating or cooling installation.

2.2 History

District energy systems have been around since the 14th century [1]. Since its inception district energy systems have utilized various energy sources including geothermal, fossil fuel, biomass and waste incineration [2]. The primary transport fluid for heat for district heating systems until the 1930s was steam; this system uses pipes in concrete ducts with steam traps and compensators, but steam at high temperatures generates large amounts of heat losses and poses a risk from steam explosions. These first systems were often used in apartment buildings to reduce the risk of boiler explosions. The second generation of district energy transport systems used pressurized hot water using water pipes in concrete, shell-and-tube heat exchangers and large valves. These systems showed inability to provide control for the heat demand but showed improvement in fuel savings. In the 1970s the third generation of district energy transport systems was developed; using pressurized water but at lower temperatures than the previous generation and often referred to as the "Scandinavian district heating technology" these systems featured prefabricated buried pipes, and compact substations and is the current system in use throughout the developed world [3]. Table 1 shows the common method of heat production and energy source associated with the technology period of the district energy system.

Table 1: Production and energy sources for district energy [3]

	1st Generation	Second Generation	3rd Generation	4th Generation
Peak Technology Period	1880-1930	1930-1980	1980-2020	2020-2050
Heat Production	Steam boilers	CHP and heat-only boilers	Large-scale CHP	Heat Recycling
Energy Source	Coal	Coal and oil	Biomass, waste and fossil fuels	Renewable sources

Coal is still used for district energy in China and recent exergetic and energetic efficiencies for those plants were calculated. In 2013, Lio et al. published an extensive analysis using the first law as well as the exergetic efficiency taking into account the chemical, thermomechanical, kinetic and potential exergy and concluded that the extraction ratio could be used as a design criteria [4]. Currently European countries are the leading users of district energy systems and have a number of countries who have made large strides to move toward sustainable district energy systems. Sweden began a transition from oil-based district heating systems to coal-based systems in 1973 due to the oil crisis [5]. Since then Sweden has increased the use of biomass to offset the current usage of fossil fuels consumed in district based heating [5]. As of 2014, 53% of the fuel mix in Sweden is biomass based [5]. Feasibility studies have been conducted on sustainable energy within district heating technologies and shown that further development is necessary to decrease losses, utilize synergies and enhance the efficiencies of low-temperature production. Renewable energy along with combined heat and power production is essential and making long term choices are important for the overall competitiveness of district heating systems [2][6][7][8].

2.3 System Identification

Identification of district energy systems are used to identify a system and how it operates. Groupings are based on several factors:

- heat transport fluid
- thermal energy transported
- heat resource used

The heat transport fluid often refers to the systems use of low-pressure steam, hot water and hot air as the primary fluid to transport thermal energy. The thermal energy transported is usually categorized in three groupings: heating, cooling, and heating and cooling. Not only is the resources utilized by the facilities but this identification also takes into account any cogeneration or polygeneration done by a district energy system. The energy sources that can be used for district heating can include fossil fuels, nuclear power, waste heat, cogenerated heat, solar thermal energy, ground source heat pumps, and biomass. Renewable energy sources particularly geothermal and solar have been effectively used in district heating in Europe, Asia and in the Americas. Cogeneration plants, often referred to as combined heat and power plants (CHP) are also key identifications of district energy systems, this is because their simultaneous generation of electricity and usable heat [1]. New technologies have enabled cogeneration to be cost effective even in smaller scale sites and a well-designed system can increase energy efficiency to over 80% [9]. Cogeneration plants can be farther identified into topping cycles and bottoming cycles. These systems can also be revised by utility cogeneration, industrial cogeneration and desalination. Waste heat identifications are used for district heating systems that take advantage of excess heat often found in industrial facilities to provide heat to nearby towns and buildings. One of the key identifications used is the density based; this categorizes the facility based on the population and building density served by the district energy system [1]. It is important to classify district energy systems for better comparison and analysis based on the characteristics and sustainable aspects. Understanding how systems are identified present opportunities for improvements to existing systems.

2.4 Energy Sources

District energy has used a number of energy sources since its beginning. Correspondingly, modern systems have been built to take advantage of heat from a variety of sources. Below in Figure 1, the energy distribution for the United States is shown, while this is not representative of every country. The figure shows how the energy sources have changed over 9 years. It is noticeable that coal and oil have decreased while nuclear has remained constant and renewable and natural gas sources have increased in use.

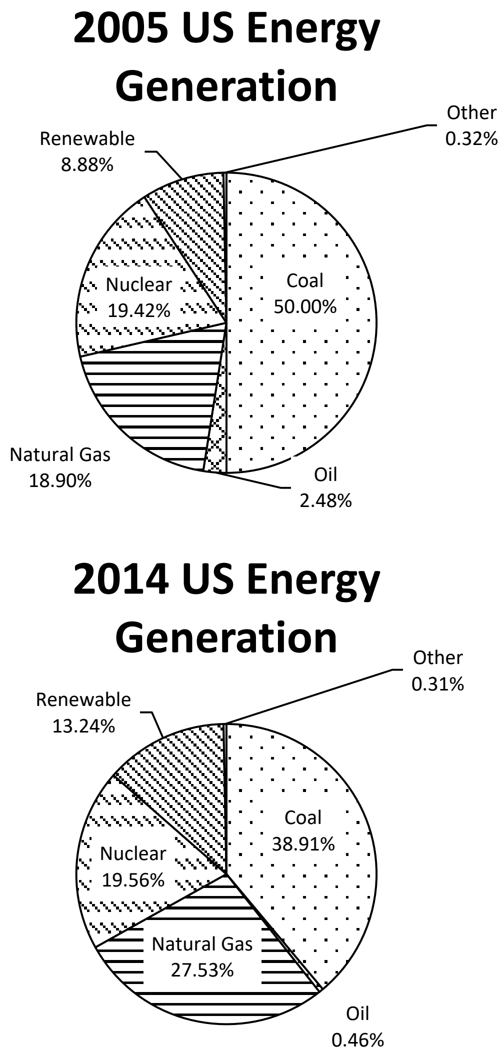

Figure 1: Comparison of Energy generation for the United States in 2005 and 2014 [10]

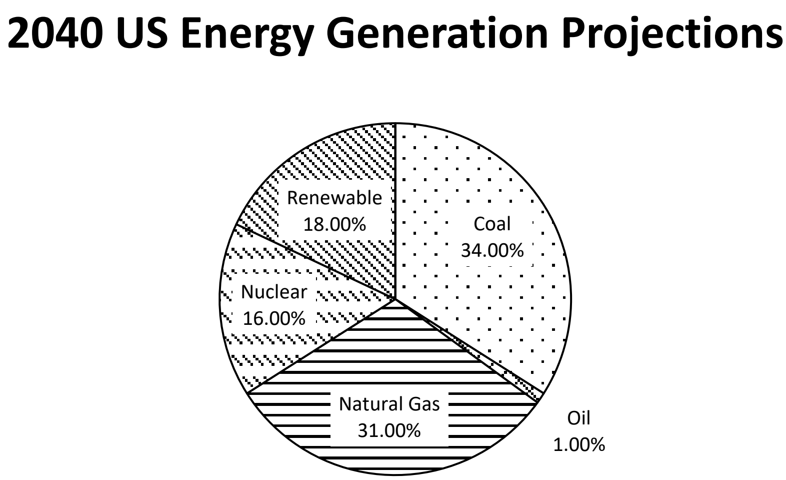

Figure 2: Projected energy generation in the United States for 2040 [11]

From comparison of Figure 1 and Figure 2 there are some interesting trends, natural gas and renewable resource usage are becoming bigger shareholders of the United States energy market. Increasing trends to cleaner energy make it is clear that consideration of these goals is necessary for the continued success of district energy systems.

Table 2 summarizes the advantages and disadvantages associated with different energy sources that can be used for district heating and cooling systems. When designing systems to take advantage of available resources, careful consideration should be given to the availability of nearby energy sources as well as their impact on the environment.

Table 2: Summary of energy sources

Source	Description	Advantages	Disadvantages
Geothermal or ground source heat pumps [12]	Built in locations above large geothermal sources, typically those with naturally occurring hot springs, geysers or aquifers	Provides year around low cost heating and cooling using district energy technology	Geologically limited and usually only efficient in moderate temperature zones
Biomass [13]	Often using wood or energy crop based material to provide heat	Renewable resource that has strong advantages in a sustainable energy future	Low Availability in many places in Europe
Waste Incineration [14]	Combustion of urban waste to provide heating to nearby buildings	Utilization of heat generated from burning waste	Potential health effects from emissions when improperly managed
Waste heat [15]	Industrial and commercial process waste heat is used	Provides excess heat to nearby buildings and is able to offset some of the normal district heating fuel costs	Usually cannot provide sole source heating, but can be coupled with an existing DH system
Fossil fuels [16]	Burning of coal, oil and natural gas to provide heat	Processes and infrastructure often already in place, reducing fuel transport costs	Large source of greenhouse gas emissions, non-renewable energy source
Solar thermal [17]	Using sunlight and solar collectors to provide high temperature water for heating and cooling purposes	Passive and active systems with the option to also provide cooling during warmer seasons using absorption chillers.	Geographic assessments as well as proper planning are necessary; variations in peak demand may significantly influence performance

Depending on a number of factors District Energy Plants would be able to provide:

- Low-temperature domestic hot water
- Heating of buildings
- Cooling using waste or excess heat
- Electricity

Each of these systems and their available options often is dependent on the local and national policies, as well as the considerations made during installation. Making informed planning and decisions about the construction and operation of district energy systems are key to insuring sustainability of these systems for future generations [3]. With increased emphasis in sustainable and green energy sources, it is important for future system designs and improvements to account for future trends and energy policies.

2.5 Design Considerations

Construction of District Energy Systems requires several factors to be considered including options for cogeneration. Specifically for industrial parks, identification of manufacturing demand and site selection are key as well as having an on-site backup thermal supply [18]. Climate should also be a consideration and it is advantageous to utilize district cooling technology in warm and hot regions [19]. Secondly selection of a furnace/burner for newly developing projects and having a large thermal output span will assist in maintaining low CO emissions [20]. Heat exchanger selection should also be considered, plate heat exchangers are especially important for geothermal heating systems, and for all systems selection of the optimal size, placement and flow rates is key to minimizing the capital cost of the district energy system install [21]. “Cost and usage of district heating systems depend on environmental and social-political contexts”. The smaller the district heating plant the higher the cost and less opportunity to utilize cogeneration technologies[22].

Poland currently uses geothermal heating technologies and economic studies of their current system show that geothermal energy costs are higher than coal but much lower than biomass, natural gas and fuel oil[23]. Cogeneration options also should be considered, biomass cogeneration is used quite often in Europe, as well as trigeneration which has been suggested to lead to emission reductions compared to fossil fuels especially in electricity generation cases [24]. Another factor to consider is power failures in combination with harsh weather conditions, there are designs of pipe networks and heat exchangers to allow the system to function with an inactive radiator circulation pump and still provide 40-80% of the heat supply in most cases [25]. For district heating systems in addition to the heating system the pipe networking should also be optimally designed [26]. Heat losses within the plant itself as well as buildings serviced by the district heating systems should be reduced in order for district energy systems to remain effective solutions [27].

By utilization of district cooling systems in the warmer months demand for district heating systems can be increased by up to 30% while maintaining a competitive edge over current electric AC options especially in locations with large excess heat supplies [28]. When considering absorption chillers, research by Udomsri indicates that thermal Coefficient of Performance (COP) is mainly effected by the electrical COP [29]. One of the locations where heating and cooling from a central plant has been evaluated is in Spain through the use of trigeneration and things like fuel and operating costs, electricity prices, tariffs and subsidies are needed to optimize payback periods [30]. A case study in South Wales, UK showed that in order to minimize the total annual energy consumption and costs variable flow and supply temperatures along with small pipe diameters and large pressure drops yielded the best results [31].

Another option for district energy systems is co-firing biogas and natural gas and utilization of cogeneration using a gas turbine and analysis shows that the influence of economic factors on the plant become more dependent as the usage of natural gas increases [32]. By placing plants in locations where energy crops and liquid manure from local farmers is accessible heat and power generation can be used by local households [33]. For wood chip biomass storage and supply chain setup are key to improving the feasibility of this fuel for district heating [34]. Using mathematical programming and optimization for forest biomass supply chains can improve the profit, costs, CO_2 emissions and fuel travel time [35]. By evaluating the most influential parameters of heat loads in district heating systems development of models that could be used to aid in predicting consumer heat loads [36]. One example of using optimization is shown by Uris et al for a biomass-fired cogeneration plant; they demonstrated a method that will maximize profitability by reaching internal return rates of up to 18% while also providing cooling in addition to heating [37]. Gebremedhim indicated that distribution costs are the primary determining factor on the feasibility of local heat and power production [38]. Using centralized control, real-time performance is shown to maximize thermal comfort in residential houses [39]. Profitability of absorption chillers is presented with 2500 to 6500 hours of yearly operation depending on the end user source [40].

System modeling and optimization have led to a number of positive outcomes in relating cost, emissions and improvement opportunities. Future research in this area needs to include emphasis on solutions for creating new district energy systems that can replace current single user systems.

2.6 Environmental Impact

With the need to reduce greenhouse emissions, careful management of energy plants should be considered to reduce the footprint that can be caused by these systems. Advantages of district energy systems have been linked to a decrease in CO_2 emissions resulting from implementation of polygeneration energy conversion technologies [41]. Chow proposed a cost-effective solution for meeting the UK's domestic 'zero carbon' goals by using a wind turbine and a district biomass boiler [42]. A paper on the design of a 100% renewable system for Macedonia concludes that it is possible to create such a system but only through the incorporation of biomass, wind and solar power [43]. Kelly and Pollitt presented the benefits of sustainable development resulting from combined heat and power district heating in the UK. These systems have the potential to prevent significant CO_2 emissions and improve the energy security of the region[6]. Utilization of biomass energy supplied to district heating systems that use woody biomass can be linked to a reduced risk of wildfire and an increase in sustainable ecology [44]. Pantaleo et al. stated that biomass heating is completive with natural gas but only where existing gas systems are already in place [45]. They also indicated that district heating is the cheapest option in low energy density areas [45]. District heating using biomass for cogeneration provides opportunities to provide electricity at a competitive cost to current energy sources [46]. Combined heating and cooling is depicted to be more efficient user of energy resources [47].

When considered as a free resource and used in district heating, Industrial excess heat usage is considered beneficial. District heating is also evaluated for population impacts by Petrov et al.; they presented scenarios and evaluations of the effects of district heating on breathing rates. Results indicate improvements in the health of the nearby population [48]. Existing system impacts can be reduced by considering opportunities for implementation of demand side management, similar to the electrical models used by cities, for thermal storage; allowing the possibility to meet heat and comfort demands [49]. When determining development of a district heating system a concept of pricing for these systems is proposed by Li et al. by utilizing demand side management to engage customers in the promotion of sustainability [50]. Another opportunity when installing these systems comes from the potential to store heat in buildings for short-term thermal energy storage [51].

New pilot systems for a net-zero exergy district energy are analyzed, one located in Östra Sala backe in Sweden. Results show that lower exergy demands in the form of heating and cooling should be matched with the lower exergy resources [52]. District cooling systems stand as an attractive alternative to conventional cooling methods; to use these benefits designing the plant requires making optimal decisions regarding chiller plant and storage capacity, as well as network size and configuration [53]. As the development of electric cars becomes more popular studies on the impact of electric vehicles on combined heat and power plants has been done using models that account for electricity, heat and the fluctuations of human need and the environment[54].

Analysis on gradual improvements of district heating technologies coupled with reductions in space heating demands demonstrates that it is crucial to continue the present development direction. District heating has a potential to foster technologies that use geothermal heating, biogas production, and solar heating [55]. Research done by Xu et al. on the development of combined cooling, heating, and power systems in China conclude that the current systems are efficient and environment-friendly[56]. Furthermore, these type of systems promise for sustainable energy technologies [56]. In addition to the environmental impacts, economic costs should also be understood and quantified [57][58]. District energy systems provide opportunities for sustainably meeting the heating, cooling and electrical demands.

2.7 Economic Feasibility

In addition to the installation considerations for district energy systems the economic effects should also be major factors in decisions. Designs should be considered with the economic aspects in mind. Selection of a system that shows large environmental benefits may in fact end up not being economical, while selection of the most economic district energy system may actually provide little, none or negative environmental benefits. Studies of systems currently in use thermal networks were shown to be financially beneficial for the high-density buildings and complexes as well as densely populated urban areas and are defined by three main factors: production costs, network costs, and connection costs [1].

Enviro-economic function is the tool to compare different energy options in district energy system by considering economic, environmental, and technology of each energy options [57]. When biomass is considered to be an unlimited resource, conversion of industrial processes to district heating systems shows a large reduction in greenhouse gas emissions according to an analysis done by Ilic and Trygg [59]. Guo et al. shows an analysis of comparison of district heating vs. individual heating in northern and southern China. Results indicate the northern region that uses district energy consumes 32% less energy per unit area. However, the infrastructure necessary to provide district heating to southern China can be very costly. In their paper they cite that residential reconstruction, heating equipment and infrastructure costs will be partially passed on to the end users dissuading the development of these systems [60].

When considering economic feasibility, retrofit implementation of district energy systems is often too costly without outside assistance. Li et al has shown advantages and disadvantages of pricing strategies in both regulated and unregulated energy markets to provide a fair cost to the consumer as well as the provider [50]. Driving factors for the competitiveness of district heating is the density of the cities they are built in. District heating has and will continue to remain competitive in high heat density city districts, but in urban areas that are spread out or contain low heat density areas alternatives to district heating are often better options [8].

2.8 Performance Analysis

When analyzing efficiency of district energy systems understanding the key components within the system is necessary. Regardless of the thermal heat source there are a number of common systems that remain similar and can easily be evaluated for both thermal and exergetic efficiencies. Figure 3 depicts a common cycle used to analyze district heating systems and the subsequent equations are the commonly accepted for energy and exergy evaluation. The energy rate balance for the cycle is presented in equation (1). An exergy rate balance equation is presented in equation (2). Exergy is considered to be the maximum work or quality of an energy source and is used to account for inputs, losses and wastes within a process and offers potential as a measure for environmental impact.

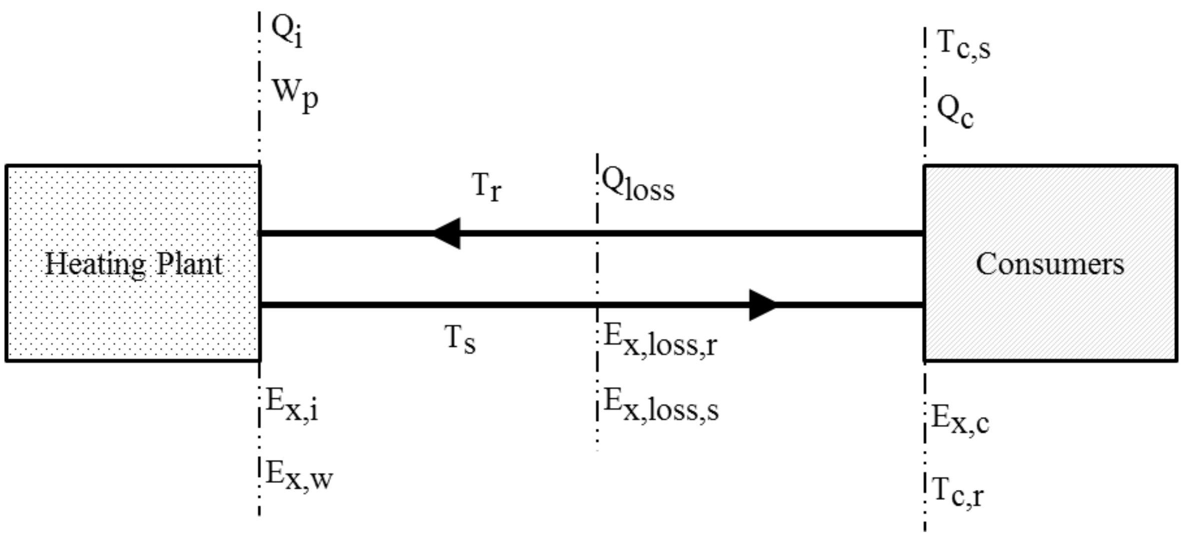

Figure 3: Common district heating cycle

From Figure 3 the energy rate balance is

$$\dot{Q}_i+\dot{W}_p=\dot{Q}_{loss}+\dot{Q}_c \tag{1}$$

And the exergy rate balance is

$$\dot{E}_{x,i}+\dot{E}_{x,w}=\dot{E}_{loss,r}+\dot{E}_{loss,s}+\dot{E}_{x,c} \quad (2)$$

Where,

Q_i is the heat added to the working fluid by the heating plant

W_p is the pump work for circulation of the working fluid

Q_{loss} is the heat loss associated with the pipe network

$T_{c,s}$ is the temperature of the fluid provided to the consumer

Q_c is the heat available for the consumer

$E_{x,i}$ is exergy added to the working fluid from the heating plant

$E_{x,w}$ is the exergy for the pump circulation of the working fluid

$E_{x,loss,r}$ is the exergy losses associated with the returning fluid

$E_{x,loss,s}$ is the exergy losses associated with the supply fluid

$E_{x,c}$ is the exergy losses associated with the heat transfer to the consumer

$T_{c,s}$ is the temperature of the working fluid returning from the consumer

In addition to heating through district energy systems, cooling is also often covered. In 1991 the United States Department of Energy published a scheme to significantly improve the performance of two stage vapor compression cycles; this was done by elimination of the rectifier resulting in a 20 to 30% higher cooling COP [61]. Lin and Yi stated that the COP of absorption chillers with minimum energy consumption can be found by optimizing return and supply temperatures [62]. In that research, energy and exergy studies have been conducted on individual components as well as whole systems in district energy systems. By evaluation of the pipe and distribution networks at a university in Turkey, the exergy losses from heat distribution, and supply and return hot water temperatures Çomaklı, et al. concluded that the most important factor affecting these losses are the supply and return temperatures [63]. For cogeneration-based district energy systems exergetic efficiencies provide a more meaningful evaluation of efficiency than energy based analysis[64]. Denmark already has approximately 50% of the electricity demand is produced by combined heat and power plants; their boiler and district heating networks, presented by Mathiesen et al., would benefit from thermal storage to enable flexible operation [65].

Exergy analysis has been conducted on a thermal energy storage system in Germany and for district energy applications by Rezaie et al. indicated that the trend of exergy efficiency of thermal energy storage from solar collection followed the trend of the storage temperature [66]. Table 3 contains the research and brief conclusions on several technologies that can increase district energy system efficiencies. Conversion of individual housing to district heat and electricity from biomass reduced the primary energy use by 88% and CO_2 emissions by 96% [67]. Human behavior led up to 50% higher heating demand than anticipated and can lead to a decrease in efficiency of a district energy system [68]. Analysis of both the demand and supply sides and their interactions are key to minimize the primary energy use in these buildings [69]. By analyzing the thermodynamic, exergetic and exergoeconomic analysis and their optimization in combined cycle power plants indicated that the combustion chamber is the most significant source of exergy destruction in a district energy plant [70].

Future improvements should be evaluated by evaluation of unit exergy cost and exergy consumption [71]. By closely matching consumer heating demand and district heating supply a reduction in exergy and energy losses occur [72]. Expansion of district heating systems to combine with current or existing energy systems improve the overall efficiency of the system [73]. Cost effective, large scale systems allow the use of solar thermal, heat pumps industrial surplus heat, geothermal heat and waste incineration to be more cost effective especially when combined with thermal storage [74]. Utilization of industrial waste heat demonstrated benefits in energy efficiency and provides base load heating for the district energy system [75].

Using thermal storage for a cooling networks at the University of Texas and optimizing its use has shown up to 17.4% energy savings [76]. Using thermal storage allows shifting in times of generation and consumption which improves the flexibility of the system [77]. Ground source heat pumps are an option for thermal energy storage. Bagdanavicius and Jenkins demonstrated that for hot water consumption reducing the room temperature set point results in a lower energy consumption for residential areas [78]. By using a centralized district energy plant environmental impacts is reduced down to 65% with an efficiency that reach 75% by using cogeneration technologies [79]. Efficiency should also be considered on a part load scenario as well [80].

Table 3: Summary of some technologies to increase efficiency

Technologies to increase Efficiency	Analysis	Conclusion
Absorption Chillers	Energy and Exergy	Optimal supply and return temperatures improve performance
Pipe Network	Energy and Exergy	Supply and return temperatures have the biggest impact of efficiency
Cogeneration	Energy and Exergy	Exergetic efficiencies provide a better analysis for performance comparisons between cogeneration technologies
Thermal Storage	Energy and Exergy	Allows for flexible operation in combined heat and power plants

Evaluations of district energy systems should take into account the total energy flow in each building to allow for the accounting of various energy supply systems [81]. Optimization of district energy systems in industrial applications often only accounts for minimizing the investment and operation costs and rarely for heating and cooling efficiencies [82]. District energy is shown to contribute to sustainability of energy supply systems [83].

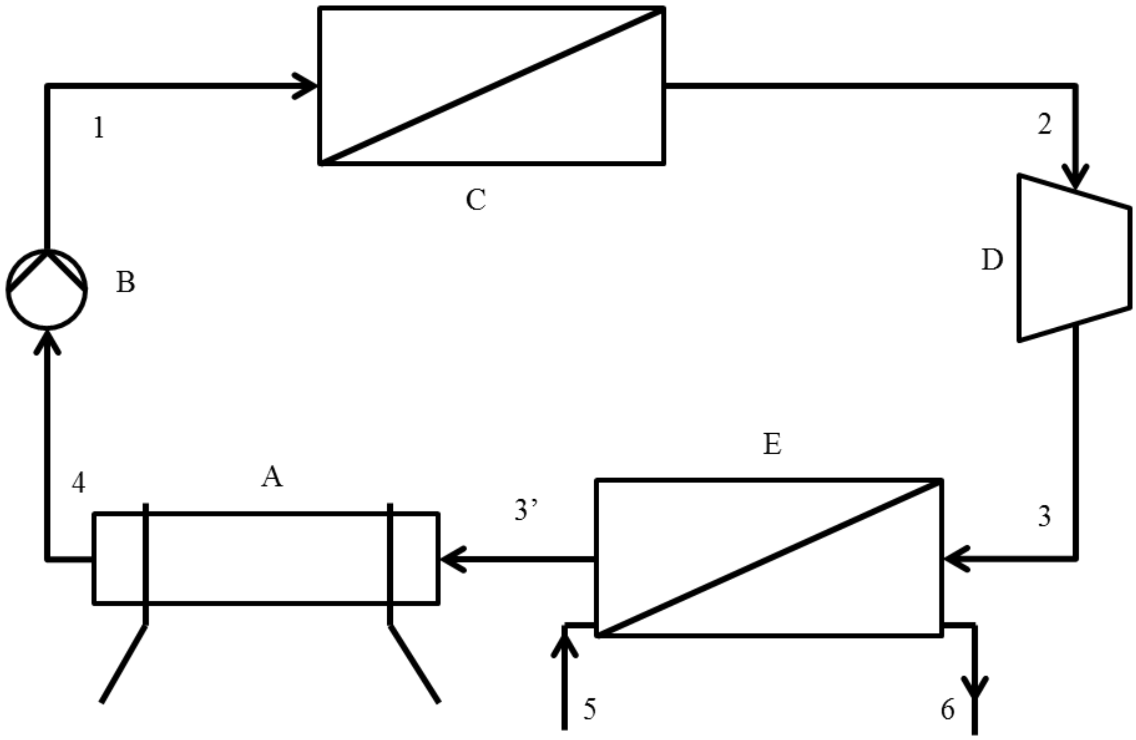

Figure 4: Rankine Cycle used for reference

Where,

A: Condenser

B: Pump

C: Evaporator – with heat input from waste heat

D: Turbine

E: Desuperheater – Provides domestic hot water

Using an analysis of heat pump technologies in district heating, Soltani et al. have shown that end users are the source of most of the irreversibility in the system at 64%. Figure 4 shows a Rankine cycle similar to the one presented by Soltani et al and used for reference for equation (3) below. By conducting energy and exergy analysis they were able to determine cold climates with lower ambient temperatures yielded higher exergetic efficiencies using the following exergy system efficiency equation to analyze the system [84]. Similar to the exergy rate balance presented in equation (2), the exergetic efficiency equation (3) is a comparison of the use of exergy to the available input to the Rankine cycle presented in Figure 4.

$$\psi_{sys} = \frac{\dot{Q}_{load}\left(1 - \frac{T_0}{T_H}\right) + \left(\dot{Ex}_6 - \dot{Ex}_5\right) + \dot{P}_{elec}}{\dot{m}_{waste,tot} ex_F} \tag{3}$$

Where,

ψ_{sys} is the exergetic efficiency of the district energy system

Q_{load} is the district space heat load of the system

T_0 is the ambient temperature

T_H is the comfort temperature for the district heat users

$\dot{m}_{waste,tot}$ is the initial mass flow rate associated with the heat input to the cycle at the evaporator (C)

ex_F is the specific exergy associated with the heat input to the cycle at the evaporator (C)

P_{elec} is the overall excess generated power from the turbine (D)

$E_{X5,6}$ is the exergy associated with the domestic water side of the Desuperheater (E)

Producing synthetic fuels from biomass are substantially more feasible when using a thermal chemical route over a electrochemical process [85]. Installation of efficient devices contribute considerably in the reduction of electric consumption of a cogeneration plant [86]. Cogeneration based from biomass sources is more energy-efficient and has less cost than individual production of heat and electricity [87]. Optimization of district heating network using the mixed integer nonlinear programming model for plant design proposed by Savola and Fogelholm provides a bases for future design schemes[88]. By using a distributed generation system the reductions in CO_2 and primary energy use is decreased by 40% [57]. Understanding and evaluating district energy performance on energy, exergy, CO_2 emissions and sustainability is paramount for future development of district energy.

2.9 Energy Policy

One of the contributing factors for the success of district energy systems is the policies that handle bioenergy. This also includes political support of research and development of bioenergy based district heating because of its potential to reduce CO_2 levels; this can also be accomplished by introducing taxes on fossil fuels [89]. The two leading countries successful in the integration of biomass systems are Finland and Sweden. This is been achieved particularly well in Sweden where long-standing policy commitments exist

[90]. There exist currently several European Union members that have potential for using these systems [90]. One of the primary design changes necessary to traditional systems requires optimal design conditions of both the building and urban area around the plant [91]. Currently there are frameworks being adopted by many countries in a push to moving toward renewable energy sources by the year 2020 and 2060 [92][93]. The energy policies are setup to curve the effects of climate change resulting from fossil fuels and are necessary to reduce greenhouse gases [94].

Investment in these systems requires financial attractiveness often this is influenced by the effect of taxes [95]. Forest biomass for District Energy often appears to be less attractive than fossil fuels due to lower prices and established cost-effective supply chains available for fossil fuels. Increased demand on forest biomass can result in negative impacts on the sustainability of the fuel source [96]. Higher electricity costs as well or lower initial investment costs are needed for small district heating networks to become an attractive alternative, this might also require the implementation of policies to encourage this transition[97]. Current European Union policies do not adequately encourage the use of this technology which is necessary to reach the 2020 goals for energy efficiency [98]. Implementation of a regional energy planning standard is necessary to bring about confidence in long term investments in renewable energy and provide the contribution to the 2020 energy goals [99]. New regulations concerning CO_2 emissions will permit investors to look at construction of new plants [100].

Using policies and subsidies to encourage wood-based fuel technologies as replacements to existing fossil fuels in short term campaigns may decrease investment risk and encourage research and design in district heating systems [101]. Promotion of biofuels is critical and can be reached through promotion and the use of subsidies [102]. Taxation policies have the potential to create favorable conditions for cogeneration and biomass-based technologies, these often are the cost-optimal solutions for district heating systems [22]. Agricultural policy has a potential to be a key factor in the bioenergy future in Europe and energy crops could potentially provide alternatives to food crops in locations where surplus food production occurs [13]. Support and promotion of excess heat utilization from industrial processes as a greenhouse gas mitigation measure[15]. In an assessment of district heating opportunities in the UK it was noted that for private companies installation of these systems pose significant risk resulting from initial costs and the uncertainty of government policies [6]. Because of the potential for monopoly powers, the regulation and pricing of distribution grids needs to be in-place to prevent abuse [103]. District heating is often debated with regards to monopolized supply; opt-out design pointed to result in larger costs for the remaining individuals within the supply area but as the cost increases often more users would opt-out in a chain reaction [104]. With sustainability and climate change being a topic of major concern today, emphasis on policies that encourage reduction in CO_2 and greenhouse gas emissions should be a must. District energy systems offer a means to a solution and should be given strong consideration when forming these policies.

2.10 Conclusions

Investigation on district heating and cooling is presented as a comprehensive review on the topics including history, identification of systems, energy sources, policy, design, environment, economy, efficiency, performance, advantages, and disadvantages associated with district energy systems. Results of research indicate that district energy systems have higher efficiency when compared with individual heating and cooling. District energy systems are often more environmentally beneficial and financially reasonable when limited retrofit is required and are cost effective for more populated areas rather than rural area. Encouraging policies are effective tools to improve the availability and quality of district energy systems through research and financial incentives. Furthermore, policies are means to shift the primary energy sources of district heating and cooling to sustainable options in environments such as renewable energy. District energy systems also open many possibilities for research on applications of new energy technologies. Moreover, there are other technologies such as thermal energy storage and absorption chiller which can be integrated into current district energy systems to increase the efficiencies of the systems. By expanding upon current research focus to include improvement in efficiencies of district energy systems and their individual components, the dependency on fossil fuels can be reduced. Potential enhancement of district energy systems are part of a sustainable energy future. Further research in the field of district energy should be focused on the technologies and policies necessary to economically transition from single user systems to environmentally sustainable district based systems.

As a final point, there are numerous opportunities toward sustainable communities which lay in district energy system. For the reason that district energy system has flexibility of changing energy resources to more environmentally friendly resources, setting up pollution limits through policies, and controlling pollutions through management of the district energy system. District energy system is the new focus for enhancing technology, business, management, environment, etc. aspects of energy management in building sectors. Consequently, district energy system is source of many opportunities for engineers in different fields, economists, investors, and policy writers.

Chapter 3: Use of Exergy Analysis to Quantify the Effect of Lithium Bromide Concentration in an Absorption Chiller

A. Lake, B. Rezaie, and S. Beyerlein, "Use of Exergy Analysis to Quantify the Effect of Lithium Bromide Concentration in an Absorption Chiller", *Entropy* 2017, 19(4), 156

3.1 Abstract

Absorption chillers present opportunities to utilize sustainable fuels in the production of chilled water. An assessment of the steam driven absorption chiller at the University of Idaho, was performed to quantify the current exergy destruction rates. Measurements of external processes and flows were used to create a mathematical model. Using engineering equation solver to analyze and identify the major sources of exergy destruction within the chiller. It was determined that the absorber, generator and condenser are the largest contribution to the exergy destruction at 30%, 31% and 28% of the respectively. The exergetic efficiency is found to be 16% with a Coefficient of performance (COP) of 0.65. Impacts of weak solution concentration of lithium bromide on the exergy destruction rates were evaluated using parametric studies. The studies reveled an optimum concentration that could be obtained by increasing the weak solution concentration from 56% to 58.8% a net decrease in 0.4% of the exergy destruction caused by the absorption chiller can be obtained. The 2.8% increase in lithium-bromide concentration decreases the exergy destruction primarily within the absorber with a decrease of 5.1%. This increase in concentration is shown to also decrease the maximum cooling capacity by 3% and increase the exergy destruction of the generator by 4.9%. The study also shows that the increase in concentration will change the internal temperatures by 3 to 7 °C. Conversely, reducing the weak solution concentration results is also shown to increase the exergetic destruction rates while also potentially increasing the cooling capacity.

3.2 Introduction

For building a sustainable system, maximizing the use of resources with minimal environmental impacts is key [105]. A completely sustainable system would require a fully reversible process, a feat that the second law of thermodynamics proves is not possible; indicating that all real processes are irreversible and impact the environment.

Approaching sustainability can yield benefits both the current and future environment [106].

Utilization of resources in a responsible fashion and with efficient methods is important when developing new technologies and analyzing current systems [107]–[110]. Conventional vapor compression systems and absorption chillers utilize different working fluids. Many of the vapor compression systems use the ozone depleting chlorofluorocarbon refrigerants (CFCs) because of the thermophysical properties offered by them. Many industrial processes often produce a significant amount of thermal energy; often by burning fossil fuels for heat or steam. Opportunities to convert waste or excess heat into useful cooling can be done by integration of absorption chilling into these systems [111].

Lake et al. reviewed district energy systems and showed trends and projections for the district energy systems. The policies, design and environmental considerations associated with heating and cooling technologies have been moving away from fossil fuels [112]. By burning fossil fuels such as coal, oil and natural gas for industrial thermal processes, the greenhouse gases (GHGs) created should be considered when the heat source is utilized by an absorption refrigeration cycle. In 2000, Hondeman performed a direct comparison of CO_2 emissions showing that as long as the Coefficient of performance (COP) of an electric chiller was greater than 6.1 the compression based cooling produced less CO_2 emissions and was more energy efficient than absorption cooling [113].

Chilled water systems are often apart of district energy (DE) systems, which have been shown to offer potential reductions in GHG emissions [114]. This can be accomplished through the use of biomass fuels, or non-carbon energy sources. Replacement of less efficient equipment with centralized heating and cooling systems will also provide reductions in GHG emissions [1]. District energy systems offer opportunities for production of hot water, low pressure steam, and chilled water for use in nearby buildings from a common central location. This is often done through the use of a production plant and underground piping systems [64].

Szargut et al. suggested that exergy methods should be considered to better realize increased efficiencies and environmental impacts [115]. Exergy is commonly considered to be the measure of work potential or maximum work that can be obtained from a system with respect to its environment or the quality of a heat source [116]–[119]. Exergy, unlike energy, is a non-conserved quantity, and exergy balances account for inputs, losses and wastes of a process [120]. Exergy input and destruction rates provide an accounting of the efficiency of resources used [121]. Dincer and Rosen have shown links between energy, exergy and sustainable development and have shown that exergy might allow for measuring impacts on the environment [122]–[125].
Lithium bromide (LiBr) absorption chillers have been evaluated based on their exergy; Gebreslassie et al. presented at detailed analysis of exergy for half to triple effect absorption chillers [117]. Bereche et al. analyzed single and double-effect LiBr systems using a thermoeconomic analysis and exergy. They were able to conclude that single-effect absorption refrigeration systems are suitable utilizing waste heat or operating in cogeneration systems because of their operation at lower temperatures compared to double-effect chillers [126]. LiBr chillers have also been internally analyzed, Morosuk and Tsatsaronis presented an exergy analysis of the internal components of absorption refrigeration machines. They were able to conclude that the absorber and generator destroy 40% of their exergy and are primary candidates for improvement [119].

The application of optimization has been applied to absorption chillers; Gebreslassie et al. assessed the relationship between heat exchange area and exergy. They used a structural method to obtain a simplified equation to estimate the optimum heat exchanger area for absorption chillers. Their analysis also concluded that in the optimum case the highest exergy destruction sources were in the solution heat exchanger and the condenser with all components decreasing their destruction rates as the heat exchange area increased [127]. Optimization of a double effect absorption chiller by Ghani et al. showed that there was a relationship between temperatures, COP and exergy. They were able to conclude that an increase in temperature in the generator yielded an increase in exergy efficiency [128].

A second law-based thermodynamic analysis of water and lithium bromide absorption refrigeration by Kilic and Kaynakli showed exergy loss rates for the major components of the chiller. They were able to conclude that the generator, absorber and evaporator were the largest sources of exergy destruction. They also showed good agreement with Ghani et al. in by increasing the heat source temperatures in the generator resulted in an increase in COP and exergy efficiency of the system [129].

Osta-Omar and Micallef created a mathematical model of a LiBr and water absorption refrigeration system. Their model incorporated an adiabatic absorber with the goal of identifying key parameters that influence LiBr mass concentrations for both strong and weak solutions. By plotting generator temperatures vs. COP, they showed that increasing temperatures in the generator resulted in a diminishing increase in COP [130].

The purpose of this paper is to develop a model to assess the University of Idaho (UI) chilled water system and determine the primary sources of exergy losses within the absorption chiller. By utilizing energy and exergy analysis models presented, methods for improving the exergy efficiency of an absorption chiller can be found by making adjustments to the LiBr concentration. Using this analysis also provides ways to evaluate efficiencies of an absorption driven chiller system.

3.3 Methodology

Using a thermodynamic approach in the case study considered here. To facilitate and insure accuracy in calculation, Engineering Equation Solver (EES) Version 9.911 was used throughout the study. State points were calculated using thermodynamic properties provided with the EES software package using measurements of temperatures, pressures and flow rates entering and leaving the absorption chiller. Aqueous lithium bromide property routines in EES are used to calculate properties internally [131]–[133]. From these values, specific enthalpy and specific entropy was evaluated. Specific exergy, exergy destruction rates and efficiencies were then calculated using those results for a steady state system. Quantification of the effect of LiBr on exergy efficiency is done by a parametric analysis on weak solution concentration.

3.3.1 Exergy

Exergy is always evaluated with respect to a dead state. This "dead" or reference state is defined at the beginning of the analyses. Useable work requires a difference between states of the system and the surrounding environment [134]. The reference state is often set by the ambient weather conditions at the time of the analysis. Exergy is always destroyed in real processes due to inherent irreversibilities, the exergy balance of a general system can be written as:

Exergy Input - Exergy output - Exergy destroyed = Exergy increase (4)

Equation (4) can be formulated on a rate basis for a steady state system; allowing for optimizing the thermodynamic system to be calculated:

$$\sum\left(\dot{X}_{Qin}-\dot{X}_{Qout}\right)+\sum\left(\dot{X}_{Win}-\dot{X}_{Wout}\right)+\sum\dot{m}(\Psi_{in}-\Psi_{out})-\dot{X}_d=\frac{d\dot{X}_{sys}}{dt}=0 \tag{5}$$

The exergy rate ($\dot{X}$) is associated with heat transfer ($\dot{X}_Q$) and work ($\dot{X}_W$) in Equation (5) are defined in Equations (6) and (7) respectively. The mass flow rate ($\dot{m}$) is multiplied by the specific exergy (Ψ) entering and leaving the system boundary and is denoted by the in and out subscripts. ($\dot{X}_d$) is the exergy destruction term and $\frac{d\dot{X}_{sys}}{dt}$ is the internal change of exergy within the system and is equal to zero at steady state conditions. T_b is the system boundary absolute temperature where the heat transfer is occurring, while T_0 is the ambient or dead state temperature:

$$\dot{X}_Q=Q\left(1-\frac{T_0}{T_b}\right) \tag{6}$$

The exergy associated with work ($\dot{W}$) is defined as:

$$\dot{X}_W=\dot{W} \tag{7}$$

The specific exergy for each flow state, the measure of the maximum work that can be generated from the flow associated with the dead state can be expressed as:

$$\Psi=h_f-h_0-T_0(s_f-s_0)+\frac{V_f^2}{2}+gz_f \tag{8}$$

Equation (8) demonstrates one of the important attributes of exergy: the amount of useful work that can be extracted from a system is measured by the maximum work by bringing the system to a state of equilibrium with the reference state [135]. The subscript *f* represents flow and is associated with the enthalpy (*h*), entropy (*s*), velocity (*V*) height (*Z*) and gravity (g). T_0, h_0 and s_0 are the dead state temperature, enthalpy and entropy respectively.

The energy efficiency (η_{en}) of the chillers considered here is a measure of useful energy is produced from a given input and can be expressed in Equation (9); for cooling cycles this is often represented as the COP. For absorption chillers, the COP is defined based on the heat transfers associated with the evaporator and the generator [16].

$$\eta_{en}=COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{gen}} = \frac{\dot{m}_{cw}(\Delta h_{cw})}{\dot{m}_{st}(\Delta h_{st}) + \dot{W}_p} \tag{9}$$

The mass flow rate of the chilled water (*cw*) and steam (*st*) are defined as $\dot{m}_{cw}$ and $\dot{m}_{st}$ respectively. Δh is the enthalpy change associated with the chilled water and steam. $\dot{W}_p$ is the electrical work supplied to the solution pump.

Exergetic efficiency (η_x) is defined in for an absorption chiller in general terms in Equation (10):

$$\eta_x=\frac{\dot{m}_{cw}(\Delta\Psi_{cw})}{\dot{m}_{steam}(\Delta\Psi_{steam}) + \dot{W}_{p,x}} \tag{10}$$

The exergetic efficiency evaluates the exergetic efficiency of the absorption chiller with $\Delta\Psi$ equal to the change in exergy of the flow of steam and chilled water. $\dot{W}_{p,x}$ is the work exergy applied to the pump.

3.3.2 Scope Definition

The scope of this assessment revolves around the absorption chiller at the UI energy plant. Evaluation of the exergy destruction rate that occurs within the chiller will be performed and the resulting impact on the utilization of steam. This chiller is steam driven using a biomass boiler. Exergy loss and life cycle irreversibility of the absorption chiller is the criterion applied and identifying exergy losses associated with using natural resources [136], [137]. For simplicity of calculation, equipment and processes for delivering wood chips to the boiler as well as pumping costs associated with the chilled water system have been neglected. Wood chip fuel for the boiler is sourced from various locations in the inland northwest region of the US and would require separate assessment as their processes vary greatly. The scope and emphasis of this assessment is solely on the production of chilled water at the UI energy plant for use in the cooling of campus. The primary focus is on the steam driven absorption chiller. The absorption chiller is not the only use of steam; however as these component operate independent of the chillers they will be neglected.

3.4 Case Study: University of Idaho Energy Plant

The University of Idaho (UI) campus in Moscow, ID, USA uses a DE system for heating and cooling. This system is composed of a biomass boiler for steam production that is primarily used for heating. The district energy plant at UI provides 120 million kg of steam annually. The 10.4 MW biomass boiler was installed in 1986 as the later part of the Clean Air act of 1963 and joint contributions from local logging companies. An Enviro-exergy sustainability analysis of the boiler has been studied by Compton and Rezaie. They were able to conclude that the boiler as a result of preheaters, economizers, and other equipment has a thermal efficiency of 76% and an exergy efficiency of 24% [138]. The boiler is designed to produce steam by utilizing wood chips from the local forestry operations. This wood is primarily western red cedar and has a higher heating value of 19.92–22.56 MJ/kg on a dry basis [37]. The steam is split between the campus demands and the absorption chiller.

A portion of the cooling needs of the UI campus are provided by a system that utilizes a steam-driven lithium bromide (LiBr) absorption chiller. The absorption chiller is classified as indirect single-effect chiller; these chillers use low pressure steam or hot water as a heat source and contain only one condenser and generator and operate under partial vacuums. During the primary cooling season the absorption chiller utilizes 27% of this steam to produce chilled water. This chilled water is utilized on the UI campus primarily for cooling. In order to meet the necessary cooling demand the University of

Idaho campus employs the use of additional electrical compression chillers as well as a thermal storage tank (TES).

The TES contains 7500 m^3 of water. This tank is charged each night and discharged during the peak heating demands of the day to reduce the less efficient usage of the electric chillers. The electric chillers operate mostly during the cool night and early morning hours to assist the absorption chiller in charging the storage tank. The chillers are staged to allow the absorption chiller to run at a full and constant capacity throughout the cooling season. When the load is greater than what is able to be provided by the absorption chiller, additional electric chillers as well as the TES are used. When the campus cooling load is less than the full capacity of the absorption chiller, the TES is used and recharged with the absorption chiller to facilitate the fully loaded efficiencies of the chiller.

The UI energy plant contains a biomass boiler, an electric chiller and the absorption chiller. A second location on campus houses the other electric chillers and the TES. Figure 5 shows the boiler and absorption chiller located in the energy plant. Saturated steam exits the boiler at 998 kPa; where the pressure is reduced to 515 kPa before the flow splits. The steam that is utilized by the absorption chiller has its pressure reduced further to 194.8 kPa while the remaining steam is sent for use on campus. The steam enters the generator portion of the absorption chiller as a superheated vapor and exits as a subcooled liquid.

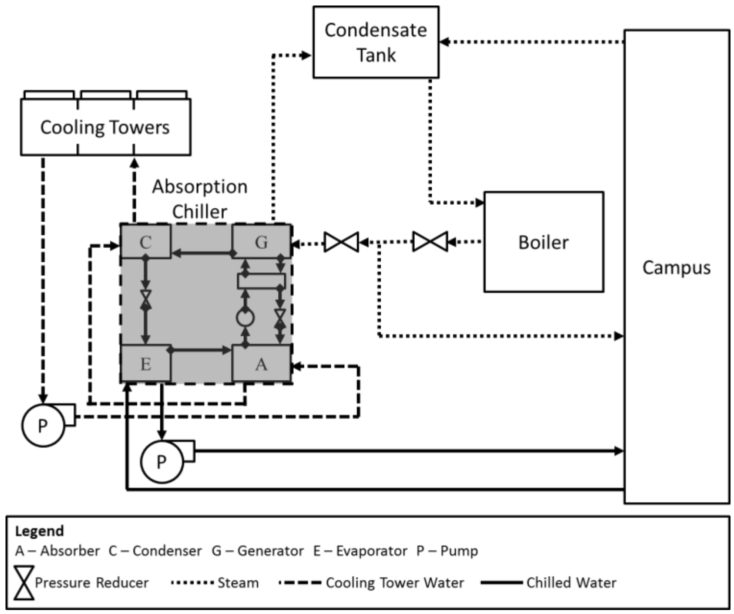

Figure 5: Simplified diagram of University of Idaho energy plant

The cooling tower is designed to be capable of returning 31 °C water during the normal operating season. Water from the cooling towers in pumped through the absorber component of the chiller before it enters the condenser component at 36 °C. The exiting water from the condenser is measured at 42 °C before entering the cooling towers.

Chilled water production from the absorption chiller is done in the evaporator. Warm water at 12.7 °C enters at 81 kg/s and exits at 6.3 °C. This chilled water is combined with chilled water produced from the other chillers and transported for use on campus through pumps. Unused chilled water is delivered to the storage tank for later use. As a result of the electric chillers and storage tank setup, the absorption chiller is allowed to operate in a nearly steady state condition.

Data was collected from the absorption chiller; this consisted of external temperatures and flow rates for water and steam as they entered and exited each component. The dead state temperature and pressure were determined at the same time as recorded measurements were taken, this occurred on 15 September 2016 at 11 am. This day was used as it represented typical operating and load conditions. A list of those values in provided in Table 4. Solution concentration is documented during routine maintenance and when periodic testing is done. Concentration evaluation is done using a hydrometer specifically calibrated for the equipment to allow adjustments of 0.5% concentration by mass.

Table 4: Measured conditions of absorption chiller on 15 September at 11 am.

Parameter	Value
Boiler	**10.43 MW**
Steam flow rate	1.3 kg/s
Steam Pressure	194.8 kPa
Steam Temperature	408.7 K
Cooling Tower	**2391 kW**
Cooling tower water flow rate	116.6 kg/s
Temperature from condenser to cooling tower	314.8 K
Temperature from cooling tower to absorber	304.3 K
Absorption Chiller	**2208 kW**
Temperature from absorber to condenser	310.1 K
Chilled water flow rate	81.0 kg/s
Chilled water entering temperature	285.9 K
Chilled water exiting temperature	279.4 K
Weak Solution Concentration	56%

In order to fully evaluate the absorption chiller performance, internal operating conditions should be known. As the equipment was not designed with internal instrumentation, a model was constructed to closely meet each condition measured externally. Using EES energy and exergy balances were performed on each component to determine exergy destruction rates.

The absorption chiller is classified as single effect; a typical cycle schematic is shown in Figure 6. The steam that the absorber uses is fully condensed and throttled to meet a chilled water temperature difference and set point. The absorption chiller operates continuously throughout the cooling season except during routine maintenance. The absorber and condenser components exhaust heat to an induced draft cooling tower which operates in a primarily dry environment. Additional chilled water loads are accomplished through the use of electric vapor compression chillers. The chilled water produced is utilized for cooling buildings and processes on campus.

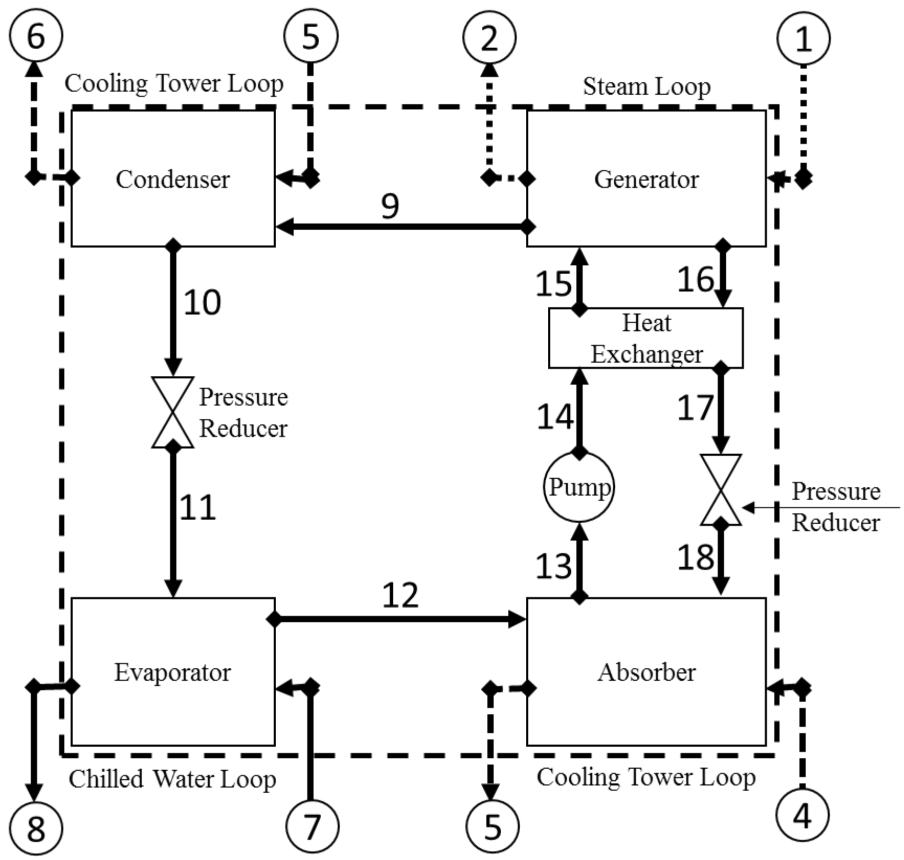

Figure 6: Single effect absorption chiller diagram (gray area from Figure 5).

A diagram of the absorption chiller is shown in Figure 6. This is typical of a single effect absorption chiller using lithium bromide as the absorbent and water as the refrigerant. This equipment operates in vacuum pressures. As a result this provides limited access to internal operation conditions. By using data collected from flows that enter and exit the components, and modeling of internal components, evaluation of exergy can be accomplished. Conditions that were measured externally and used for the analysis are shown in Table 4. State 1 is defined by a measured temperature and pressure of the superheated steam entering the generator. State 2 is calculated from measurements at state 3 and state 1. State 3 is defined by the temperate and atmospheric pressure of the condensate return tank.

Currently the University of Idaho records data digitally at 5 min intervals for the equipment analyzed in this assessment. Steam flow rate is measured on the condensate return side of the absorption chiller. Both steam pressure and temperature are recorded just prior to entering the generator component of the chiller. Cooling tower flow rates are measured by the circulation pumps, and temperatures are recorded just outside of the absorber and condenser components. Chilled water flow rates are also measured at the pumps and temperatures are measured at the inlet and exits of the evaporator by the control system of the chiller. Solution concentration is measured and adjusted during routine maintenance cycles.

To assist in the evaluation of the absorption chiller a numerical model was created in EES. The model was designed to approximate the internal conditions that match external values. Using the model to study on the evaluation of the current state of exergy destruction could be assessed for each component as well as the overall system. As the primary focus of exergy associated of the absorption chiller is evaluated, the height component of the physical exergy in Equation (8) is assumed to be relatively small or negligible for this situation.

3.5 Analysis

Using Equation (5), the absorption chiller is analyzed with the environment conditions of the chiller: a dead state temperature of 300.0 K and a pressure of 101.7 kPa. Using the equations of state provided by the EES software package, energy balances and Equation (5) for exergy analysis, the thermodynamic properties of each state point have been summarized in Table 5. The points listed in Table 5 are referenced to those points labeled in Figure 6 where state points 1–8 are based on the external measured values and 9–18 are calculated using the model. Values of enthalpy, entropy and exergy presented in the table are referenced to a common datum or reference point within EES.

Table 5: Data for flows and conditions for the absorption chiller when T_0 = 300.0 K, P_0 = 101.7 kPa. State point 0 is the dead state values, states 1-18 refer to Figure 6.

Point	$\dot{m}$ (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg-K)	ψ (kJ/kg)
0	-	300.0	101.7	112.7	0.39	-
1	1.3	408.7	194.8	2739.0	7.22	598.5
2	1.3	362.9	194.8	376.1	1.19	26.8
3	1.3	362.9	101.7	376.1	1.19	26.7
4	116.6	304.3	101.7	130.4	0.10	104.7
5	116.6	310.1	101.7	154.7	0.18	105.5
6	116.6	314.8	101.7	174.5	0.24	106.5
7	81.1	285.9	101.7	46.5	−0.19	105.5
8	81.1	279.4	101.7	26.4	−0.26	106.6
9	0.9	348.6	7.4	2641.0	8.11	236.7
10	0.9	313.2	7.4	167.5	0.22	106.1
11	0.9	275.9	0.8	167.5	0.26	95.7
12	0.9	275.9	0.8	2506.0	8.73	−83.4
13	8.8	305.9	0.8	82.4	0.06	0.2
14	8.9	305.9	7.4	82.37	0.06	0.2
15	8.9	335.7	7.4	143.3	0.25	4.7
16	7.9	363.2	7.4	223.3	0.37	11.8
17	7.9	326.5	7.4	155.2	0.18	2.5
18	7.9	308.8	0.8	155.2	0.18	1.2

For modeling purposes it is assumed that the chiller operates in a steady state condition. Internally, states 9 through 12 are considered pure water with the assumption that the water leaving the condenser is a saturated liquid and leaving the evaporator as a saturated vapor. As the cooling tower is oversized for the equipment currently in place, excess heat is always removed from the flow. Each component is considered adiabatic with respect to the other internal components. States 13 through 15 contains a mixture of lithium-bromide and water at a weak solution and states 16 through 18 a strong solution. Pump work is considered constant and operates based upon manufacturing specs and operating conditions.

When developing a model of the absorption chiller several factors were taken into account. To insure accuracy of the model all state points were referenced to a common datum point. In EES many of the Lithium-Bromide equations of state have separate reference points from water and needed to be addressed before calculation of properties.

Evaluation of the exergy destruction within the absorption chiller was calculated using Equation (5). Each component was evaluated individually as well as the chiller as a whole. Then using the model, a prediction could be made of potential improvements to reduce exergy destruction within the chiller and improve the overall sustainability. Table 6 shows a list of the equations used for evaluation of the exergy destruction rates for each of the components.

Table 6: Exergy destruction rate expressions and values for the system and its components.

Component	Equation	Exergy Destruction Rate (kW)
Condenser	$X_{des,Cond} = \dot{Q}_{cond.}\left(1-\frac{To}{T_{10}}\right)+\dot{m}_9(\psi_9-\psi_{10})$	240.5
Refrigerant Valve	$X_{des,Rvalve} = \dot{m}_{10}(\psi_{10}-\psi_{11})$	9.7
Evaporator	$X_{des,Evap} = \dot{m}_{11}(\psi_{11}-\psi_{12})+\dot{Q}_{Evap.}\left(1-\frac{To}{T_{12}}\right)$	41.7
Absorber	$X_{des,Abs} = \dot{m}_{12}\psi_{12}+\dot{Q}_{abs.}\left(1-\frac{To}{T_{13}}\right)+m_{18}\psi_{18} - m_{13}\psi_{13}$	265.1
Pump	$X_{des,P} = \dot{m}_{13}(\psi_{13}-\psi_{14})+\dot{W}_{p,x}$	1.6
Solution Heat Exchanger	$X_{des,SHX} = \dot{m}_{14}(\psi_{14}-\psi_{15})+\dot{m}_{16}(\psi_{16}-\psi_{17})$	34.8
Generator	$X_{des,Gen} = \dot{m}_{15}\psi_{15}+\dot{Q}_{gen.}\left(1-\frac{To}{T_{16}}\right)-m_{16}\psi_{16} - m_9\psi_9$	266.4
Solution Valve	$X_{des,Svalve} = \dot{m}_{17}(\psi_{17}-\psi_{18})$	10.4

Evaluation of the exergetic efficiency and exergy destruction of the absorption chiller and its components were done within the model. Shown in Equations (11) and (12) are the equations used to calculate the COP and exergy efficiency, respectively:

$$COP = \frac{\dot{m}_7(h_7-h_8)}{\dot{m}_1(h_1-h_2)+\dot{W}_p} = 0.65 \tag{11}$$

$$\eta_x = \frac{\dot{m}_7(\Psi_7-\Psi_8)}{\dot{m}_1(\Psi_1-\Psi_2)+\dot{W}_{p,x}} = 15.6\% \tag{12}$$

Using the model, additional analysis can be done; evaluation of energetic and exergetic efficiencies as well as performance predictions can also be made for each of the components. By using a model that approximates the internal system, changes to various components and concentrations can be made to gain potential insight. Predicting improvements made in exergy destruction rates present potential changes that warrant farther testing or experimentation.

3.6 Results and Discussion

Overall the absorption chiller on the University of Idaho campus is responsible for an exergy destruction rate of 870.1 kW. Using the model analysis the dominant sources of exergy destruction are the condenser (27.6%), absorber (30.5%) and generator (30.6%). The exergy efficiency is estimated to be 15.6% and a COP of 0.65. Improvement in these components is directly related to the internal processes as well as the physical heat exchanger design.

Changing the heat exchangers is often difficult and costly, especially when a chiller is already in operation; but adjustment to the internal composition of lithium-bromide and water may yield lower cost improvements. To provide potential improvements to the current system evaluation of the influence of various concentration percentages is needed. This is done by selecting an assessment range to cover from 52% to 62% lithium-bromide by mass. Higher concentrations beyond 62% yielded strong solution concentration percentages too close to the crystallization line and would result in potential damage to the equipment. The minimum solution concentration was chosen to explore the results lower than the suggested operation range for the chiller at the University of Idaho.

To evaluate the variations in the model it was assumed that the available heat from the steam could not change, this is because the current steam production and usage at the University of Idaho is not easily adjustable. It is also assumed that the temperature entering the absorber component is constant since the cooling tower is always able to meet the demands of the chiller and return the appropriate water temperature. Figure 7 shows the impact of concentration adjustment on the exergy destruction rates of the major components. As concentration increases the absorber, condenser and evaporator decrease their exergy destruction rates while the generator and the solution heat exchanger (SHX) increase their exergy destruction rates.

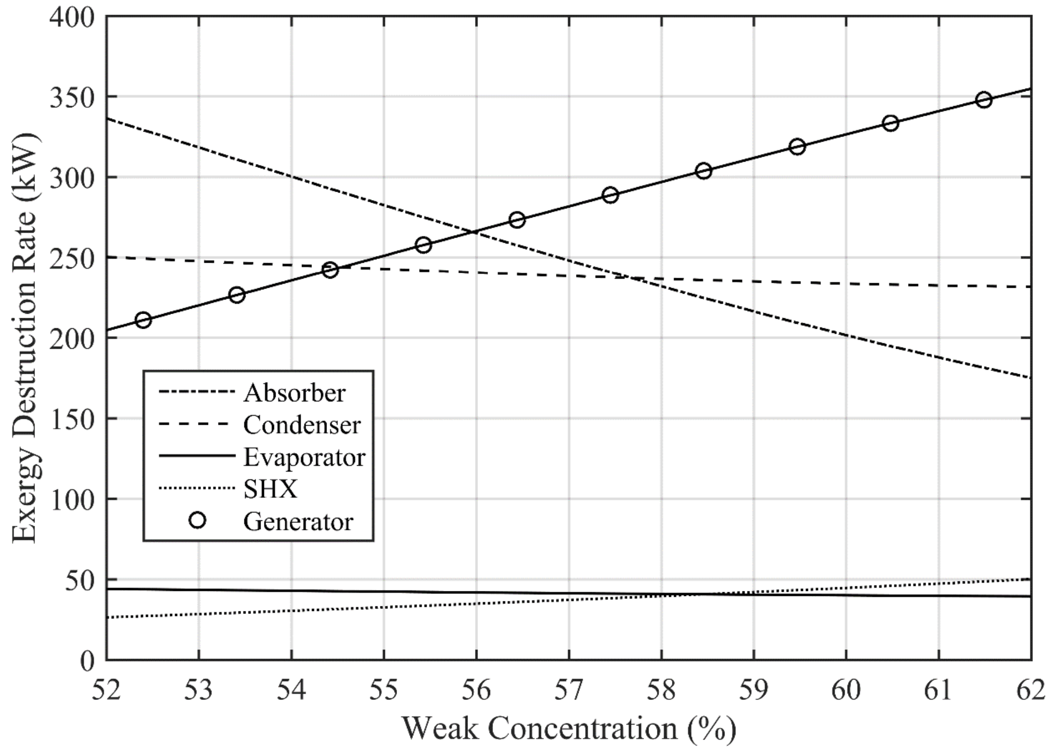

Figure 7: Exergy destruction rate as a function of weak solution concentration.

The solution pump and valves are not shown as their contribution to the overall exergy destruction is minimal. Comparison of individual components provides insight into the inner workings of the chiller. As the solution concentration increases more heat or higher temperature steam utilization is necessary to drive off the water into the refrigerant side. This increased heat gain by the remaining now strong solution causes a higher temperature differential in the solution heat exchanger yielding a greater destruction rate.

The generators exergy destruction rate is expected to increase proportional to the change in concentration as it requires more heat to drive an equivalent amount of water out of the LiBr solution. Likewise, the absorber benefits from these changes, as the strong solution is more efficiently able to return to a weak solution, this is shown by the decreasing exergy destruction rate.

The condenser is shown to decrease its exergy destruction rate as the concentration increases. As the higher temperature facilities better heat transfer to the cooling tower loop. Fluid conditions exiting the condenser are constant. This is a result of the cooling tower being oversized for the equipment using it. The influence of this causes the Evaporator to have minimal changes over the range of study.

The SHX increases its exergy destruction rate as a result of the larger temperature differential that occurs from the higher generator output temperatures.

Changing the solution concentration has an effect on cooling capacity, shown in Figure 8. The analysis shows that in increase in maximum cooling capacity is expected as the concentration is reduced from 56%. By increasing the concentration of lithium-bromide the maximum capacity decreases. This change is nearly proportional to the increase in concentration.

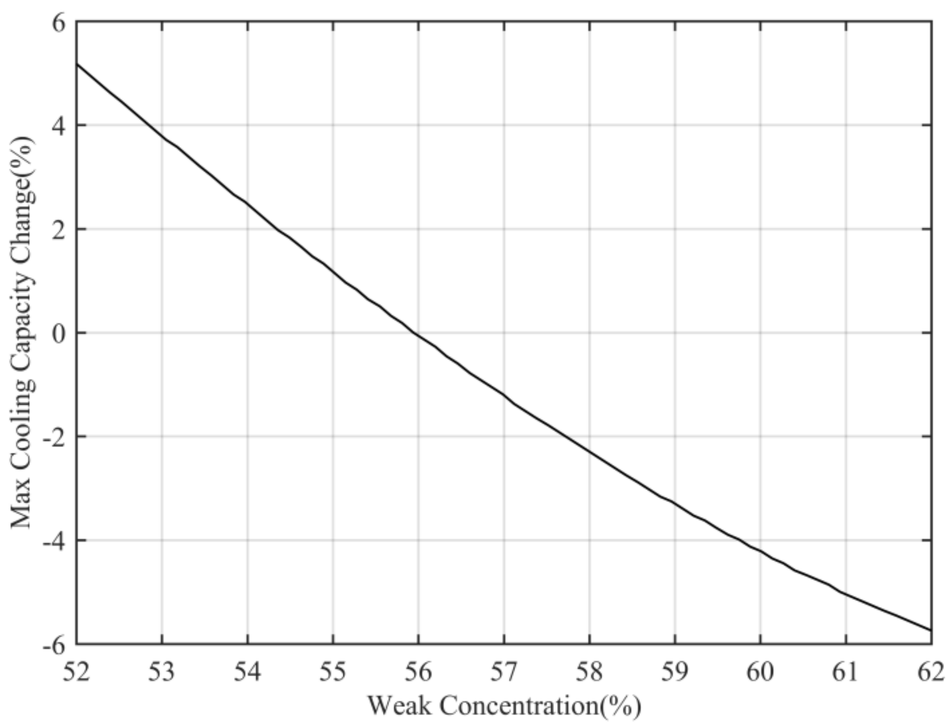

Figure 8: Percent change in cooling capacity as a function of weak concentration.

Total exergy destruction, shown in Figure 9, a minimum point is expected in the 57%–60% range; as the chiller is designed to operate in this area. Temperatures, heat sources, flow rates, and heat exchangers were designed for these operating ranges and adjustments significantly outside of this region would not typically be available. The total exergy destruction rate indicates a minimum at 58.8% lithium-bromide concentration; this would result in a decrease of exergy destruction rate of 0.4% and a decrease in the maximum cooling capacity by 3%.

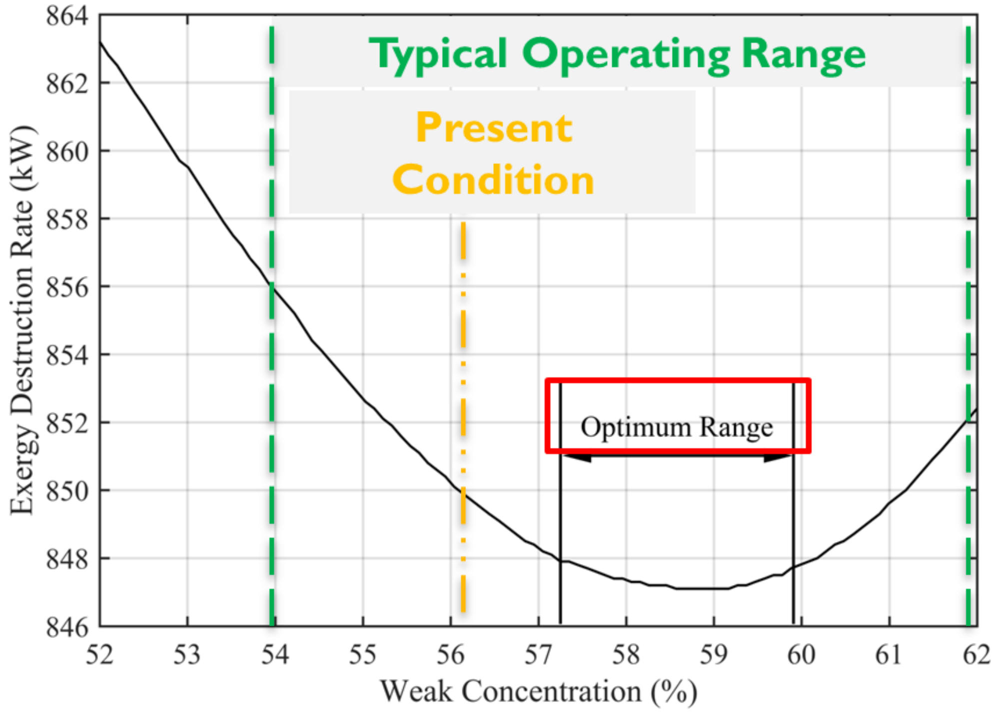

Figure 9: Total exergy destruction rate as a function of weak concentration.

At the optimum point the increase of 2.8% concentration results in an increase in the temperatures primarily at the generator as shown in Table 7. The increase in temperatures reflects trends seen in operation of the chiller.

Table 7: Temperature changes associated with increasing the solution concentration by 2.8%.

Point	Location	Temperature Increase (°C)
9	Leaving the generator (Refrigerant)	5.9
15	Entering the SHX (Weak Solution)	3.7
16	Entering the generator (Weak Solution	7.0
17	Leaving the generator (Strong Solution)	2.5
18	Leaving the SHX (Strong Solution)	5.5

By predicting increase in temperatures that will result of this change verification of the results can be done through measurement of the temperature rise associated with the generator and solution heat exchanger. It is expected that the generator should increase in temperature of 5 °C and the solution heat exchanger should increase by approximately 4 °C. These temperature increases result in an overall change in the exergy destruction rates of all the components, as shown in Table 8.

Table 8: Exergy destruction rates for minimum.

Component	Exergy Destruction Rate (kW)	Percent Difference (%)
Condenser	235.3	−0.48
Refrigerant Valve	9.4	−0.03
Evaporator	40.4	−0.13
Absorber	219.8	−5.13
Pump	1.6	0.00
Solution Heat Exchanger	41.5	+0.78
Generator	308.4	+4.94
Solution Valve	10.8	+0.06

The increase in temperatures results in a decrease in exergy destruction in the condenser, absorber and evaporator. The generator, solution heat exchanger and solution valve increase in exergy destruction rates as a result of the higher temperature of the strong solution. The increase in temperatures also result in a higher temperature or flow rate provided to the cooling tower as additional heat must be extracted in the condenser. This increase should be considered when the cooling tower operates in conditions near its capacity.

3.7 Validation

Using the model analysis the dominant sources of exergy destruction are the condenser (27.6%), absorber (30.5%) and generator (30.6%). The model conclusion also compares well with the analysis of exergy destruction rates presented by Morosuk and Tsatsaronis. They indicated that the absorber and generator should be the primary focus for improvement [119]. Morosuk and Tsatsaronis were able to identify that the heat exchangers that contained both the highest temperature differences as well as the mixing and separation of LiBr and water should generate the most exergy destruction in the system. This is also identified by the model results. However, since the model is constructed for a specific system, the operating parameters and conditions will differ. In order to validate the model, the model was setup to predict flow rates and temperatures at several points to compare to the given data, shown in Table 9.

It is shown that the largest error in the model relates to the flow rates of the boiler steam and the cooling tower water. This is expected as the model assumptions do not account for fouling within the chiller. Shown in Figure 10, the fouling within the absorption chiller can significantly influence temperatures and flow rates. The chilled water remains the most accurate as the fluid properties on both sides of the heat exchanger are water.

Table 9: Comparison of model for validation.

Quantity	Measured		Model		Error
Boiler					
Steam flow rate	1.3	kg/s	1.26	kg/s	3.46%
Cooling Tower					
Cooling tower water flow rate	116.6	kg/s	113.2	kg/s	2.92%
Absorption Chiller					
Temperature from absorber to condenser	310.1	K	310	K	0.03%
Chilled water flow rate	81	kg/s	81.1	kg/s	0.12%
Chilled water entering temperature	285.9	K	285	K	0.31%
Chilled water exiting temperature	279.4	K	279	K	0.14%

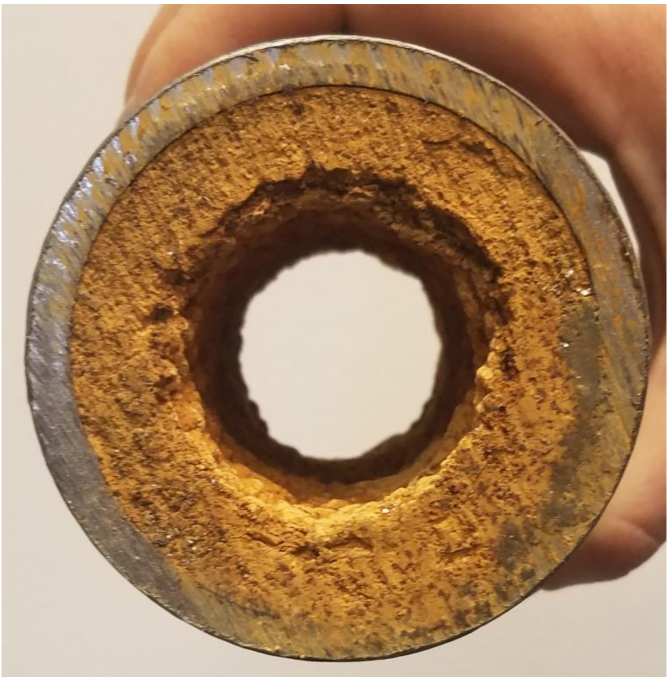

Figure 10: Fouling on replaced piping in absorption chiller.

3.8 Cost Savings

By reducing the exergy destruction of equipment, less exergy is needed to accomplish the same task. As a result of the staging of the chillers and TES on the UI campus the absorption chiller is able to run constantly at full capacity. By relating the exergy destruction improvements to a steam cost, savings can be found in biomass fuel used by the boiler. The internal cost of operation for the steam production is estimated to $8.95 per thousand kg of steam. The exergy destruction rate of the absorption chiller is shown to be 0.4%. With the generator using an annual 40 million kg of steam the reduction in equipment operation, fuel and electric costs associated with this change is estimated to yield $1798 of annual savings.

3.9 Conclusions

This study demonstrates the value in analyzing current systems to evaluate for potential improvements. Understanding an absorption chiller even under current operating conditions can yield insight into the components that yield the greatest exergy destruction. In order to drastically improve the exergy destruction rates of the absorption chiller in use by the University of Idaho, changes to the heat exchangers must be made. Improvements to the performance of the heat exchangers can be accomplished by changing the frequency of the maintenance schedule or by replacing the current equipment. Replacement can be a costly solution. Many studies have presented that heat source temperature for the generator can be a driving influence in the performance of the chiller. This solution is difficult as the UI boiler system and steam usage on campus requires specified temperatures and pressures for operation. By optimizing the concentration of lithium-bromide, a potential low cost option, improvements can be made in the exergy destruction rates.

Using measurements taken from a steam driven absorption chiller a mathematical model was used to analyze and identify the major sources of exergy destruction within the chiller. It was shown that the absorber, generator and condenser contribute the most to the exergy destruction at 30%, 31% and 28% respectively. The Parametric studies of the model revealed a minimum exergy destruction rate with an optimum concentration of 58.8%. This 2.8% concentration increase resulted in a net decrease of 0.4% of the exergy destruction caused by the absorption chiller. This change also decreased the exergy destruction within the absorber by 5.1%. The increased concentration was also shown to decrease the maximum cooling capacity by 3% (65 kW) and increase the exergy destruction of the generator by 4.9%. When the cooling capacity is decreased the COP is decreased. When the steam flow rate is decreased the COP is increased. The net change to the COP remains unchanged while the overall exergy efficiency increases.

While the model is unique to the UI campus absorption chiller, the significance of obtaining the optimal range of any absorption chiller would yield insight unique to that chiller. Each model would be useful for monitoring and predicting practical operating parameters. Expanding the scope of this assessment to include the impact on the boiler system as well as the chilled water production would provide the full impact of this change in concentration. Each absorption chiller and energy plant is different and this configuration and exergy assessment show the impacts of the change in lithium bromide on the absorption chiller but a full accounting of all the systems is necessary for a comprehensive picture of the impacts of this analysis.

By reducing the exergy destruction rate, sustainability improves. While small, the improvement require little to no additional hardware adjustments to the current system and the increased temperatures caused by this adjustment will utilize the more of the available cooling tower capacity. Changing the concentration of a lithium bromide absorption chiller should be done in small increments. Adjustments to concentrations will result in impacts on the whole chilled water and steam system and additional consideration should be given to the changes on the pumping costs associated with these results.

Chapter 4: Energy and Exergy Efficiencies Assessment for a Stratified Cold Thermal Energy Storage

Forthcoming in *Applied Energy*

4.1 Abstract

Cold Thermal Energy storage systems (TES) present opportunities for offsetting peak demand from chillers. An assessment of the TES system at the University of Idaho was performed to quantify the current exergy efficiency of single phase water based Cold TES that typically operates under the full capacity. Internal temperatures within the TES vary from 7°C and 15.5°C throughout the summer months. Measurements were taken on internal temperatures and flow rates and were used to create a model in TRNSYS. Comparison of Richardson, Fourier Peclet, and Biot numbers show the influence of internal and external conditions on TES performance and stratification characteristics. The Richardson number indicated that the turbulence effect of the inlet geometry is very small and it has negligible effect on the stratification within the TES. The Peclet and Fourier numbers showed that prediction of the stratification profile of a TES can be done with minimal measurements. The Biot number showed that the temperature variation only occurred vertically within the TES. Using the data obtained, as well as analysis of the model showed the TES is determined to have an overall energy efficiency of 75% and an exergy efficiency of 20%. The individual layers of the TES were evaluated to conclude that the upper half of the TES is the most exergy efficient layers of the TES and steps to maximize their usage should be taken without reducing the overall capacity.

4.2 Introduction

Resource utilization with minimal environmental impacts is key to building sustainable systems [105]. While a completely sustainable system would require a fully reversible process, impacts on the environment can still be reduced. Approaching full sustainability benefits both the present and future environment [106]. Making use of resources in a responsible fashion is important and it should always be considered when developing new technologies or analyzing current systems [107]–[110].

District energy (DE) systems offer opportunities for reductions in greenhouse gasses (GHGs) through the use of biomass fuels, or non-carbon energy sources [114]. Reductions in GHGs can also be accomplished by replacement of less efficient equipment with centralized heating and cooling systems often found in district energy plants [1]. Lake et al. reviewed district energy systems and showed trends and projections for future district energy systems. These policies, design and environmental considerations associated with heating and cooling technologies and their shift away from fossil fuels to more sustainable energy sources [112].

Szargut et al. suggested that exergy methods should be considered To better realize the impact of increased efficiencies on the environmental [115]. Exergy is commonly considered to be the measure of potential work or maximum work that can be obtained from a system with respect to its GHGs in the environment or the quality of a heat source [116]–[119]. Exergy, unlike energy, is a non-conserved quantity, and exergy balances account for inputs, losses, and wastes of a process [120]. Dincer and Rosen have shown links between energy, exergy and sustainable development and they have shown that exergy might allow for measuring impacts on the environment [122]–[125].

Often used in conjunction with district energy systems, thermal energy storage (TES) systems offer the ability to store thermal energy in a medium for later use. There are three types of TES systems, sensible, latent and thermochemical. Sensible TES often utilizes water or rock, while latent utilizes phase changes (e.g. water/ice). Thermochemical storage makes use of inorganic substances as the storage medium. The medium used depends on the storage period, economic viability and operating conditions [139]. Liquid water is commonly used for the sensible system as a result of its characteristics of being non-toxic, easily obtainable, contains a high thermal capacity and for its high range of temperature availability.

One common method for evaluation of sensible heat TES systems involves the stratification within the storage medium. Stratification occurs mostly in air or liquid mediums and most of the applications occur in water supply systems. Thermal stratification has been studied within tanks since the 1970s showing that the stratification can improve the performance of the energy storage [140]. A fully stratified tank is shown to be better than a fully mixed water tank by up to 6% in storage efficiency and exhibits improvements in the whole system by up to 20% [141].

Stratification aspects have been studied including the influence of flow rate on the stratification degree, inlet geometry on mixing and the effect of thermocline on the efficiency of the TES system [142]. During use, the heated water is discharged from the top inlet port of the TES and cold water is removed from the bottom outlet. This process results in a thermal stratification from the temperature variation. The temperature variation results in a density variation within the water resulting in a separation of hot and cold water by gravitational effects. This region is called the thermocline. The efficiency of a TES increases as the temperature difference between the top and bottom increase and performance are improved by maintaining the stratification of the fluid [140], [142]–[147].

Several energy and exergy studies have been performed for TES systems. Li has shown evaluations of sensible heat TES systems and he was able to conclude that these systems are one of the most efficient ways to store thermal energy. Li also addressed the major influencing factors in TES performance are including flow rate and geometry [148]. Rosen et al. analyzed the effect of stratification on energy and exergy capacities in thermal storage. They were able to show that an increase in exergy storage capacity is attained in thermal storage stratification. They concluded that the use of stratification in TES design should be considered as it increases exergy storage capacity [149]–[154].

Exergy analysis has been advocated by Rosen and Dincer for the study of thermal systems. They emphasize that exergy analysis is necessary to assess performance improvements and for optimization of processes [155]. Rosen et al. also indicate that exergy analysis approaches provide intuitive advantages for cold TES systems [156]. Rismanchi et al. reviewed much of the work in energy, exergy and environmental aspects in 2012 showing that cold TES systems are highly energy efficient often above 90%. They also noted that the exergy efficiencies were below 20% and provide a more realistic evaluation of the irreversibilities within TES systems [157].

This paper provides a detailed analysis of the cold TES system at the University of Idaho (UI), the Moscow campus and reports on the data acquisition, modeling process, and exergy analysis. The data acquisition describes the measurements taken and procedures necessary to create a model representative of the current TES system. TRNSYS is used for modeling the system to identify and evaluate the exergy and performance of the TES system. The results of the paper are valuable as they highlight the methods necessary to evaluate a TES system under incomplete cycles of discharge and charging and the effects on performance and exergy. This paper also suggests improvements to the current system increase performance and efficiencies. The results should be applicable to many chilled water systems that have significant variation in day to day loads during the peak cooling season.

4.3 Methodology

Thermodynamic approach is used for study the case study. To ensure accuracy in calculations, TRNSYS 17 is used throughout the study. Evaluation of the TES system is conducted using data collected on-site in 2016. Temperatures and flow rates are used to determine the internal energy, for the exergy analysis. This is compared with inlet and outlet flows of the TES system in the form of exergy efficiencies. TRNSYS 17 was used to model the current system and simulate the performance for purpose of predictions on changes within the current system.

4.3.1 Exergy

Exergy is always evaluated with respect to a dead state. This “dead” or reference state is defined at the beginning of the analyses. Useable work requires a temperature difference between states of the system and the dead state [134]. The reference state is often set by the ambient weather conditions at the time of the analysis. Exergy is always destroyed in real processes do to inherent irreversibilities, the exergy balance of a general system can be written as:

$$\text{Exergy Input-Exergy output - Exergy destroyed} = \text{Exergy increase} \qquad (13)$$

Equation (13) can be formulated on a rate basis for a steady state system; allowing for optimizing the thermodynamic system to be calculated:

$$\sum\left(\dot{X}_{Qin}-\dot{X}_{Qout}\right)+\sum\left(\dot{X}_{Win}-\dot{X}_{Wout}\right)+\sum\dot{m}(\Psi_{in}\text{-}\Psi_{out})-\dot{X}_{d}=\frac{d\dot{X}_{sys}}{dt} \quad (14)$$

The exergy rate ($\dot{X}$) is associated with the exergy rate of heat ($\dot{X}_Q$) and work ($\dot{X}_W$) in equation (2) are defined in equation (15) and (16) respectively. The mass flow rate (ṁ) is multiplied by the specific exergy (Ψ) entering and leaving the system boundary and is denoted by the in and out subscripts. ($\dot{X}_d$) is the exergy destruction term and $\frac{dX_{sys}}{dt}$ is the internal change of exergy within the system. T_b is the system boundary absolute temperature where the heat transfer is occurring:

$$\dot{X}_Q = Q\left(1-\frac{T_0}{T_b}\right) \quad (15)$$

The exergy associated with work ($\dot{W}$) is defined as:

$$\dot{X}_W = \dot{W} \quad (16)$$

The specific exergy for each flow state, the measure of the maximum work that can be generated from the flow associated with the dead state can be expressed as:

$$\Psi = h_f\text{-}h_0\text{-}T_0(s_f\text{-}s_0) \quad (17)$$

Equation (17) demonstrates one of the important attributes of exergy: the amount of useful work that can be extracted from a system is measured by the maximum work by bringing the system to a state of equilibrium with the reference state [135]. The subscript f represents flow and it is associated with the enthalpy (h), entropy (s). T_0, h_0 and s_0 are the dead state temperature, enthalpy and entropy respectively.

The change of exergy associated with the TES between the inlet (a) and outlet (b) is shown in equation (18).

$$\Delta\Psi_{b-a} = \dot{m}_a C[(T_b - T_a) - T_0 \ln(T_b/T_a)] \quad (18)$$

The internal exergy change of the TES from initial (i) time to final (f) time is shown in equation (19).

$$\Delta X_{int} = m\left[\left(u_f - u_i\right) - T_0\left(s_f - s_i\right)\right] \quad (19)$$

The mass of water in the TES (m) is multiplied the by the change in internal energy (u) within the tank. The exergy efficiencies for charging ($\eta_{x,C}$) and discharging ($\eta_{x,D}$) are shown below in equations (20) and (21).

$$\eta_{x,C} = \frac{\Delta X_{int_C}}{\Delta \Psi_C} \tag{20}$$

$$\eta_{x,D} = \frac{\Delta \Psi_D}{\Delta X_{int_D}} \tag{21}$$

Where $\Delta X_{int,C}$ and $\Delta X_{int,D}$ are the internal changes in cold thermal storage during the charging (C) and discharging (D) respectively. The overall exergy efficiency, η_x is shown in equation (22).

$$\eta_{x} = \frac{\Delta \Psi_D}{\Delta \Psi_C} \tag{22}$$

4.3.2 Stratification Modeling

Thermal stratification is a complex physical process affected by geometrical structure, and operating conditions, some of which cannot be easily described in a model [140]. There are a number of equations that are useful in obtaining information about a TES. Three useful non-dimensional numbers are: Peclet (Pe); Biot (Bi), and Richardson (Ri) [158].

The first calculations needed to be accomplished are the Reynolds number (Re) and the Prandtl number (Pr). Density (ρ), velocity (V), diameter of the tank (D_i), viscosity (μ) of within the tank are used in the calculation of Re:

$$\mathrm{Re} = \frac{\rho \cdot V \cdot D_i}{\mu} \tag{23}$$

Pr is calculated using specific heat (C), viscosity (μ), and conductivity (k) of the fluid. Pr is dependent primarily on the fluid used by the TES with Low Pr numbers (Pr = 9.7 for water used in cold TES systems) extended stratification when compared to high (Pr>33 [140]) values which cause stratification to present more like a piston movement when viewing the isotherms.

$$\mathrm{Pr} = \frac{C \cdot \mu}{k} \tag{24}$$

Larger Peclet numbers indicate an increase in internal heat transfer. This is calculated by multiplying Reynolds number (Re) by the Prandtl number (Pr).

$$\mathrm{Pe} = \mathrm{Re{\cdot}Pr} \tag{25}$$

A smaller Biot number indicates a more efficient storage, however the modified Biot number (Bi_m) is used as it accounts for axial conduction effects and is calculated using the convective value (h_o), the length or height (for vertical cylindrical tanks) of the tank (L), the conductivity of the wall (k_w) and the wall thickness (δ) [140]. For Bi_m small numbers indicate the tank walls will be a higher temperature than the coldest part of the storage tank, while large numbers the better the thermal stratification within the tank will be [159].

$$Bi_m = \frac{h_o \cdot L^2}{k_w \cdot \delta} \tag{26}$$

Richardson number (Ri) is another way to assess the turbulence effect of inlet geometry as shown by Ghajar and Zurigat et al. They showed that for Richardson numbers less than 3.6 inlet geometry has a significant influence on stratification [160] [161]. When Richardson numbers are greater than 10 the inlet effects can be neglected [162]. Van Berkel et al. showed that for Richardson numbers from greater than 10 to 20 clear mixing appears [163],[140]. Ri is calculated using the following equation. Where Grashof (Gr) number is composed of the density (ρ), thermal expansion coefficient (β), gravity (g), temperature difference within the tank (ΔT), the height of the tank (H), and viscosity (μ).

$$\mathrm{Ri} = \frac{\mathrm{Gr}}{\mathrm{Re}^2} = \frac{\rho^2 \cdot \beta \cdot g \cdot \Delta T \cdot H^3}{\mu \cdot Re^2} \tag{27}$$

The last dimensionless number used is the Fourier number. This is calculated by using the thermal diffusivity (α), time (t), and height (H). This is used for the transient aspects of the TES.

$$\text{Fo} = \frac{\alpha \cdot t}{H^2} \tag{28}$$

The Fourier number is multiplied by the Peclet number to identify the thermal profile of the TES system over a non-dimensional height.

The thermal capacity (E) and maximum thermal capacity (E_{max}) of a TES can be calculated by the integral of the TES tank with respect to the vertical direction (z) where the elements integrated are slices of the TES tank. It is assumed that there is no temperature variation between the centerline and the wall, this assumption can be validated by the Biot number. The cross sectional area (A), density, heat capacity of the TES are multiplied by the difference of the temperate at a vertical point (T(z)) and the maximum return temperature of the TES (T_{max}). This equation is integrated in the vertical direction with respect to dz from the bottom of the tank (0) to the top of the TES, or its height (H).

$$\text{E}, \text{E}_{max} = \int_0^H \rho \cdot C \cdot A \cdot (T(y) - T_{max}) dz \tag{29}$$

The maximum capacity is calculated when T(z) is set equal to the minimum supply temperature throughout the entire TES.

4.3.3 TRNSYS Model

TRNSYS modeling was done by utilization of the cylindrical storage tank model (Type 534). This was tied into modules that provide incoming temperatures and flow rates that were provided from the data measured during this analysis. During the setup, many of the variables needed to be defined included loss coefficients and inversion mixing flow. The loss coefficients used in this study reflect data obtained from the asbuilt documentation of the TES for an insulated aluminum construction of an above ground tank. The inversion mixing flow addresses the rate at which temperatures between nodes interact. A value of 0 allows for inversions within the tank to exist, while a value less than 0 causes instantaneous and adiabatic mixing between nodes at the end of each time step.

The process necessary to create a working model that closely emulated the TES system required comparison of the temperature profiles as well as the energy changes within the TES. The initial starting points were established from known operational parameters and through the evaluation of the model these values were adjusted to allow for a more accurate model of the process.

In order to make use of the data provided from TRNSYS, the data for each node was evaluated using the mathematical equations provided in the exergy and stratification modeling sections. These post-processing methods included evaluation of the exergy efficiencies of the model and their comparison to the real data obtained.

The ambient conditions of the TES are based upon measured temperatures and solar gains that occur during typical charging and discharging cycles. These conditions are used for quantifying heat transfers at the wall of the TES; they are also used for the dead state calculations in the exergy analysis.

4.4 Case Study: University of Idaho Cold TES

The University of Idaho campus in Moscow, Idaho, USA uses a DE system for heating and cooling. This system is composed of a biomass boiler for steam production that is primarily used for heating. The cooling demand load of the UI campus are provided by a system that utilizes a steam-driven lithium bromide (LiBr) absorption chiller. The absorption chiller is classified as indirect single-effect chiller; this chiller uses low-pressure steam or hot water as a heat source and contains only one condenser and generator; this equipment operates under partial vacuums. The district energy plant at UI provides 120 million kg of steam annually. This steam is produced by a biomass boiler that utilizes wood chips from local forestry operations. This wood is primarily western red cedar and has a higher heating value of 19.92-22.56 MJ/kg on a dry basis [164]. The biomass boiler is responsible for 95% of the steam production, Compton and Rezaie analyzed this system and showed that the boiler has a thermal efficiency of 76% and with an exergy efficiency of 24% [138].

This steam is split between the campus heating demand, laboratory uses and the condensing steam absorption chiller. During the primary cooling season, the absorption chiller utilizes 27% of this steam to produce chilled water. This chilled water is utilized on the UI campus primarily for cooling. Figure 11 shows the information that is available to the TES operators. A commercial control software is used to monitor the stratification temperature and it provides estimates for the thermocline location as well as charging and discharging rates based on defined parameters. The software package also contains the controls and parameters necessary for the operation of the campus cooling and heating equipment.

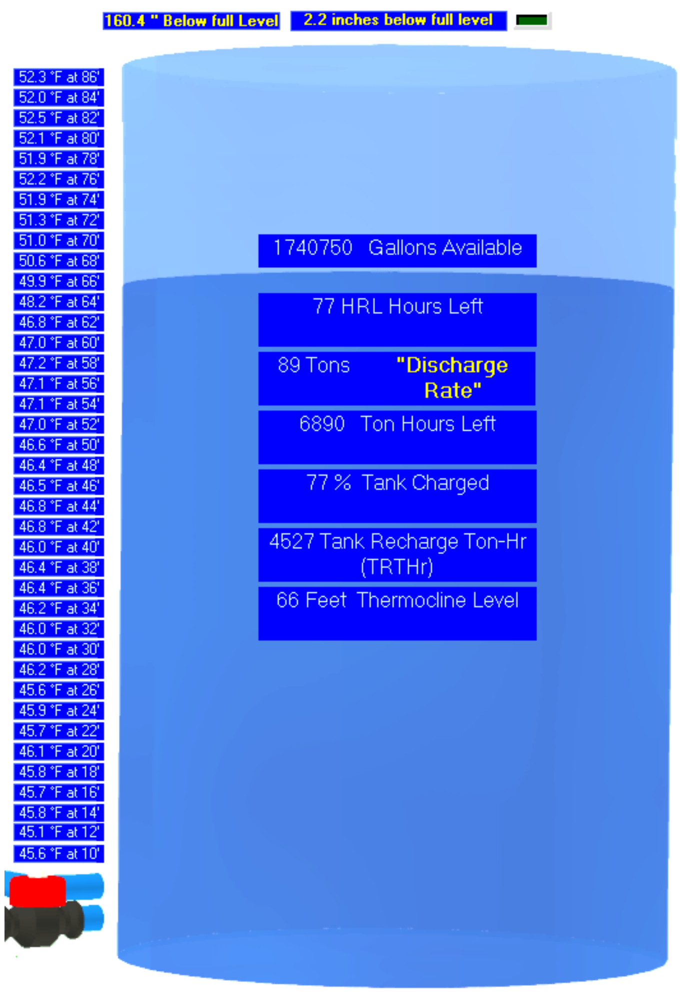

Figure 11: Image capture of software package used by operators

In order to meet the necessary cooling demand load, the UI Moscow campus also employs the use of 3 electrical compression chillers as well as a cold thermal storage tank. The TES is an above ground sensible storage tank containing 8,780 m^3 of water.

This tank is charged each night and discharged during the peak heating demands of the day to reduce the less efficient usage of the electric chillers. The electric chillers operate mostly during the cool night and early morning hours to assist the absorption chiller in charging the storage tank.

Figure 12 shows outdoor, supply, return and mean temperatures associated with the TES during operation. Overall analysis of the TES on the UI Moscow campus is done using data logged on 5-minute intervals throughout the primary cooling season as well as data obtained during the cooler months for comparison. This plot shows the temperature profiles over a 17 day time span to provide insight into the dynamics both within and outside of the TES system.

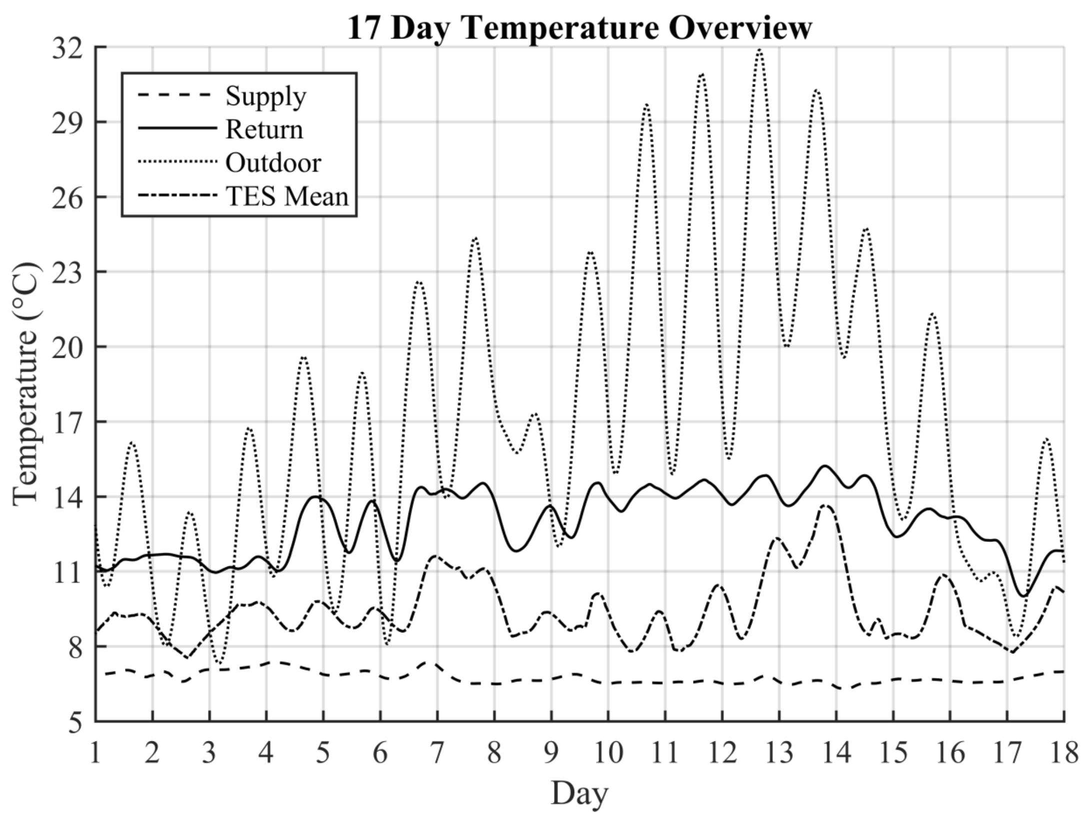

Figure 12: Outdoor and TES temperatures

The supply temperature remains consistent, while the return temperature changes significantly throughout the day as a damped version of the outdoor temperature. The TES mean provides a visual metric of the TES capacity. When the TES Mean temperature is near the return temperature the TES has nearly exhausted its cold storage, while temperatures near the supply temperature indicate a near full state. The TES is designed using an inlet and outlet ports located in the center line of the tank near the top and bottom as shown in Figure 13. The supply and return sides both have diffusers to slow the flow and reduce mixing. The return and supply side correspond to those presented in Figure 12. During charging warmer water is removed from the return side and chilled water is supplied to the supply side. During discharging chilled water is drawn from the supply side and then returned as warm water to the top of the tank.

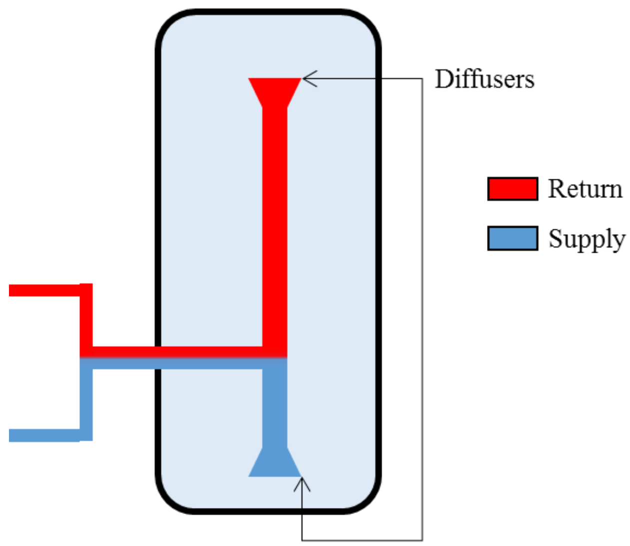

Figure 13: Simplified cold TES flow diagram.

4.5 Analysis

4.5.1 Stratification Analysis

The identification of the non-dimensional numbers allows for quick assessment of potential operation expectation of a TES. Table 10 shows the parameters used in the calculations of the dimensionless numbers. The non-dimensional numbers are shown in Table 11 for the UI Moscow campus cold TES based upon the equations 11-16.

Table 10: Parameters calculated for the UI Moscow campus cold TES

Parameters	Value	Units
ρ	1000	kg/m^3
V	6.16E-04	m/s

D_i	7.93	m
μ	1.34E-03	kg/m-s
C	4.2	kJ/kg-K
k	0.574	W/m-K
δ	0.051	m
kw	22.85	W/m-K
h_o	2.483	W/m^2-K
L, H	26.2	m
β	7.44E-05	1/K
α	1.38E-07	m^2/s
ΔT	8	^oC
t	10	hour

Table 11: Dimensionless numbers and their values.

Dimensionless Number	Description	-
Bi	Horizontal temperature profile between centerline and wall	1470
Fo	Used with the biot number in transport phenomena analysis	7.20E-06
Gr	Ratio of buoyancy to viscous forces within a fluid	3.28E+12
Pe	Product of Reynolds number and Prandtl number	33079
Pr	Ratio of momentum diffusivity to thermal diffusivity	9.759
Re	Used to predict laminar to turbulent transition in flows	3390
Ri	Impact of inlet flow on stratification	285727

The Bi is large, meaning that the tank will have better the thermal stratification and that the fluid near the tank walls will be similar to the centerline temperature. This affirms the assumption that there is no temperature variation between the centerline and the wall of the TES, this was used in the formulation of equation (29) when calculating thermal capacity. Re is indicating that the internal flow turbulence is low, but not laminar. The Gr is used with Re to calculate Ri. Ri is very large also indicating that the inlet flow has little to no effect on the tank [140]. Ri number also quantifies the effectiveness of the diffuser plates, by reducing incoming flow velocities to eliminate incoming flow effects that typically result from high velocity jets and turbulent flow. The Pe indicates the amount of internal heat transfer when multiplied by Fo a value of 0.2388 is calculated. This result indicates the temperature stratification profile for the

TES tank. Shown in Figure 14 the TES system should have a temperature profile sharing similarities with 0.166 and 0.332.

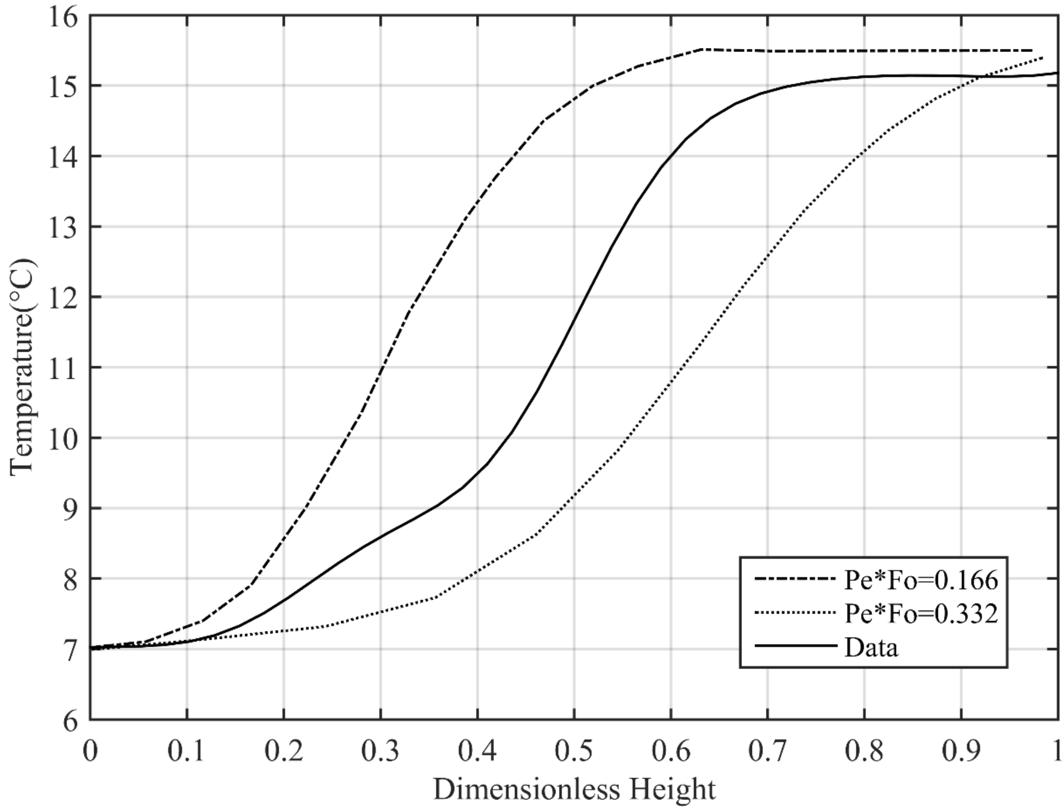

Figure 14: Evaluation of Peclet and Fourier Numbers for TES systems [159]

This expected temperature profile is useful when looking at the data obtained limited measurements. This is useful by allowing for an approximation of the temperature profile. This profile can be used in conjunction with measured internal temperatures to interpolate temperatures between measured values. The Pe×Fo number also provides an opportunity to predict the temperature profile. Shown in Figure 14 the Pe×Fo numbers of 0.166 has a steeper temperature profile than the measured system with a more constant temperature above the thermocline which occurs between 0.2 and 0.6., while a Pe×Fo number of 0.332 indicates a larger or longer thermocline area with a fair amount of mixing that occurs in the upper portions of the tank.

4.5.2 Empirical Model

Measurements of the temperatures are recorded throughout the 2016. For the evaluation of the TES system, it is analysis in summer and winter separately, because the condition of cooling load is is different in these two seasons. Figure 15 shows the profiles of the TES system based upon its maximum capacity of 3.131E8 kJ. This is calculated by the designed temperatures of the TES system: 7°C supply temperature, and 15.5°C return temperature using equation (29).

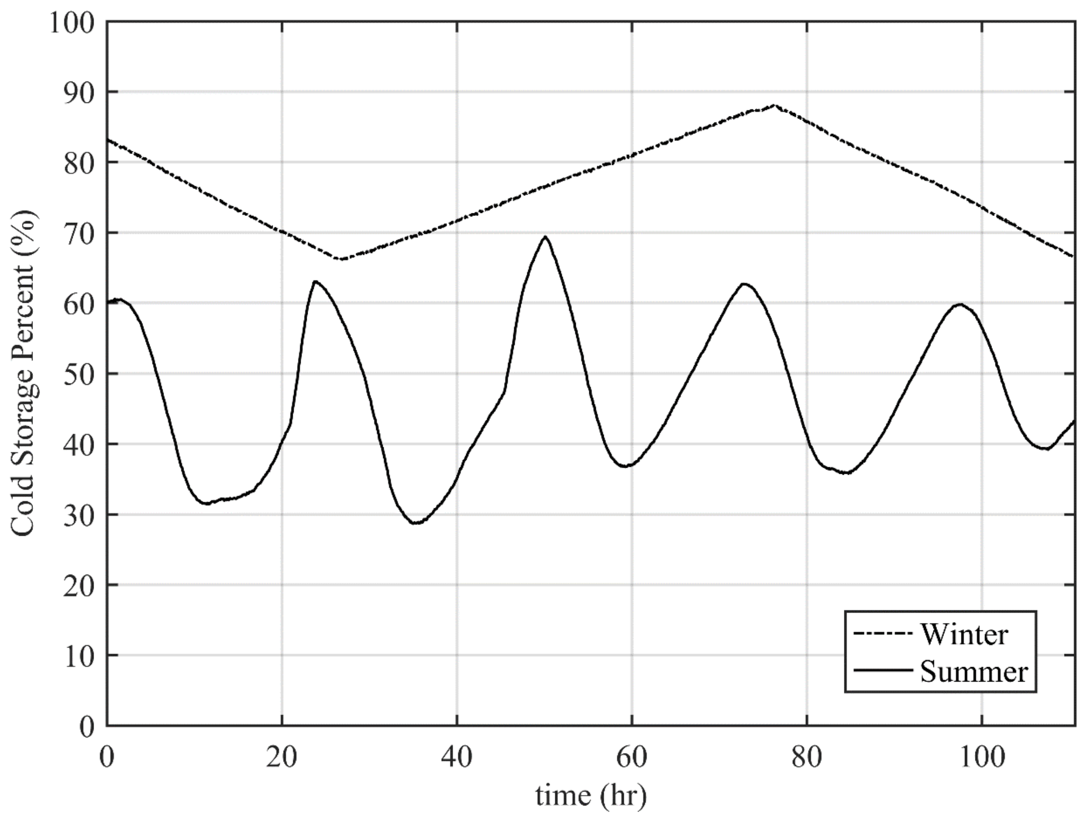

Figure 15: Percent of total cold storage capacity in the summer and winter

It is also shown that during the summer usage the TES system is around 60% of the maximum cold storage capacity. The winter profile shows is from a second data set obtained during the late fall and winter months. As the demand for cold storage is quite low, fewer chillers were used during the charging process resulting in a slower charging profile. Data measurement during both the summer and winter are considered here as they can provide insight into the TES performance characteristics with regards to outdoor and environmental conditions.

The recorded temperatures are plotted for a charging and discharging cycle. The temperatures shown are at various fixed points within the TES and are labeled in accordance to their height from the bottom of the TES. This cycle is based upon the percentage of the full cold capacity of the chiller. The TES Storage capacity used in this paper refers to the current thermal capacity of the TES divided by the maximum thermal capacity of the TES expressed in a percent where each value is calculated using equation (29). By using the percent capacity several aspects can be observed; vertical lines indicate a temperature change with little to no change in internal storage, while horizontal lines indicate an overall change in internal storage while no change in temperature. The horizontal lines also show what sections of the TES are currently passive during the charging and discharging processes.

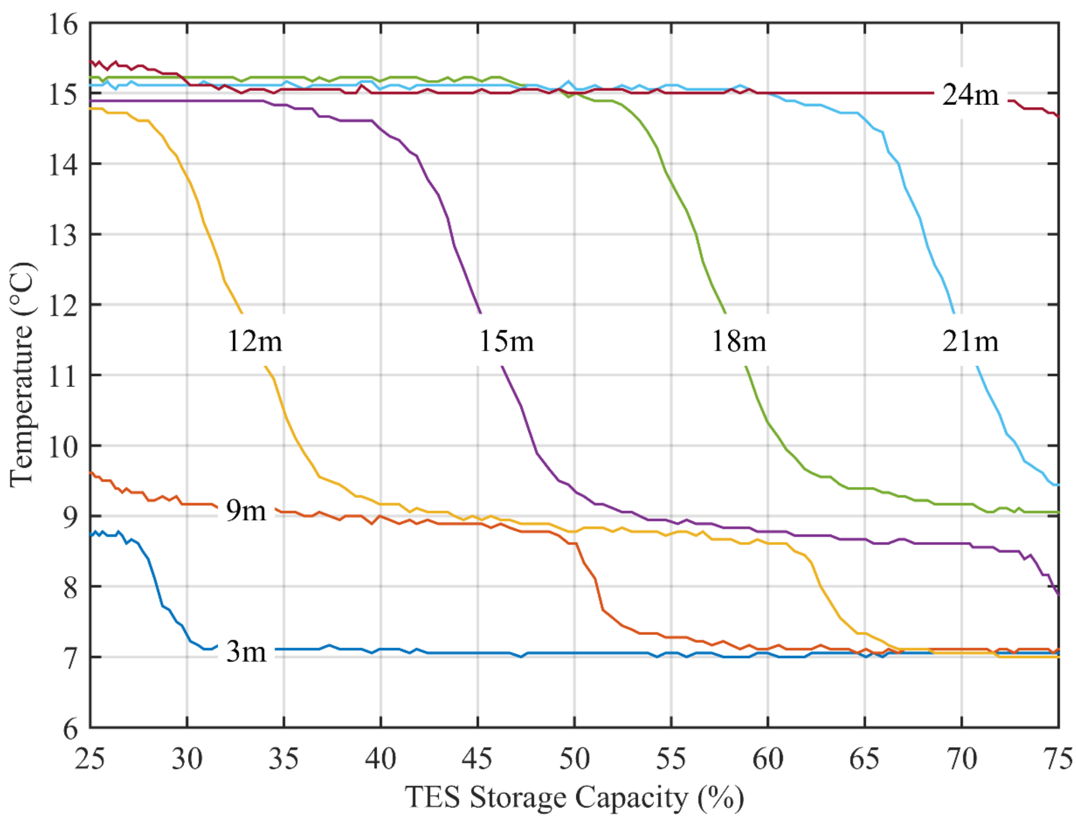

Figure 16: Temperature profiles of TES during charging

The temperature profiles in Figure 16 shows several trends during the charging process. First, the TES diffusers located at the bottom/inlet of the system are creating a second smaller thermocline region in the lower section of the tower. These regions show to be influenced by the regions 6 meters above. This charging cycle occurs over a 12 to 13 hour period starting at 9 pm at night, upon reaching 9 am the TES system was estimated to be 78% capacity. At that point, a discharge cycle would then begin as shown in Figure 15.

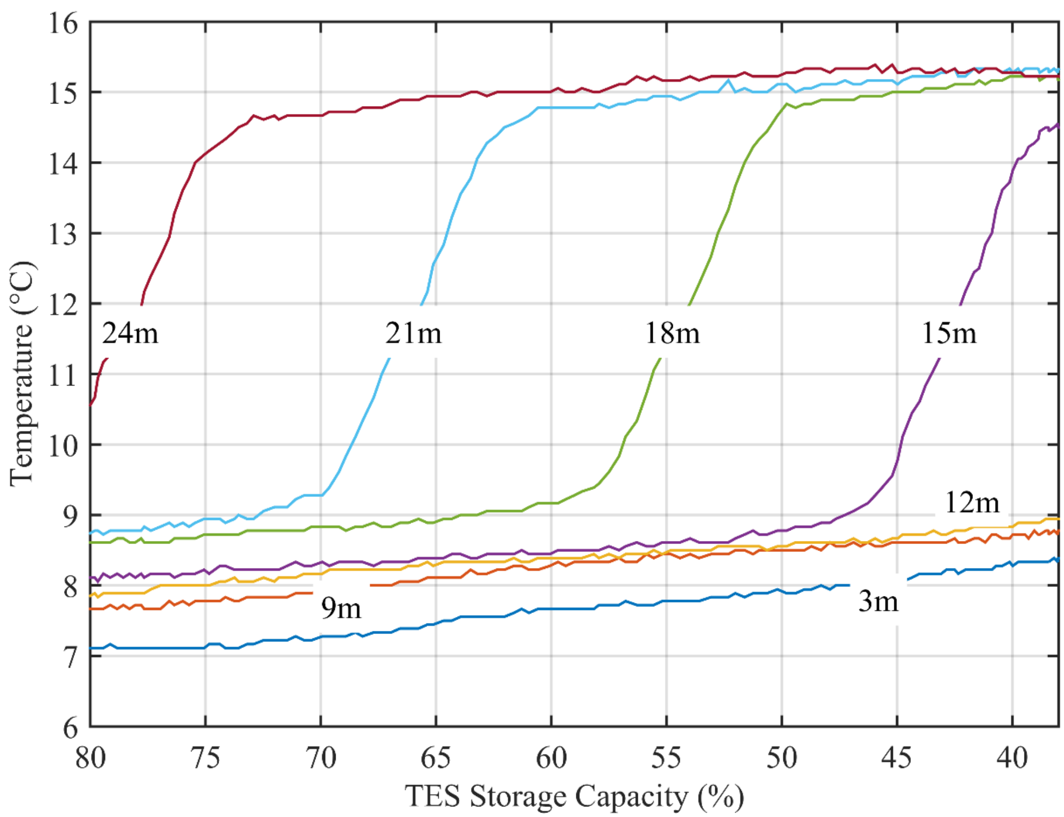

Figure 17: Temperature profile of TES during discharging

During a discharge cycle, as shown in Figure 17, temperatures across all regions of the tank increase. This is the result of the lower diffusers influence on the flow leaving the bottom of the TES storage tank as well as external heat gains that occur throughout the day.

4.5.3 TRNSYS

The purpose of utilizing TRNSYS was two-fold. As a result of the incomplete cycling that occurs during use, it is difficult to assess the full performance of the TES. By creating a model that mimics the TES and using the real data gathered to compare and validate the model, prediction of the full cycle can be done. TRNSYS stratified TES models function on mass flow and temperature inputs coupled with initial internal temperatures and construction composition to simulate their usage. The model uses outdoor temperatures to predict heat gains and losses on the external wall of the tank. Adjustments to inversion characteristics allow for simulation of the internal interactions within the stratified layers as well as simulation of a fully mixed model. Fully mixed models are useful for showing the advantages of stratified storage.

The TRNSYS model for charging was setup using the initial conditions provided from the data recorded in the actual TES system. To create a model that performed similarly to the actual TES system was obtained by adjusting the mean flow rate, fluid properties, and inversion characteristics to more accurately represent the processes observed in the TES system. Shown in Figure 18 the charging model temperatures are shown. By plotting the temperature vs the total cold capacity of the TES system it shows that the model differences from the actual data in Figure 16 occur mainly in the region near the incoming diffuser side (3 m and 9 m lines).

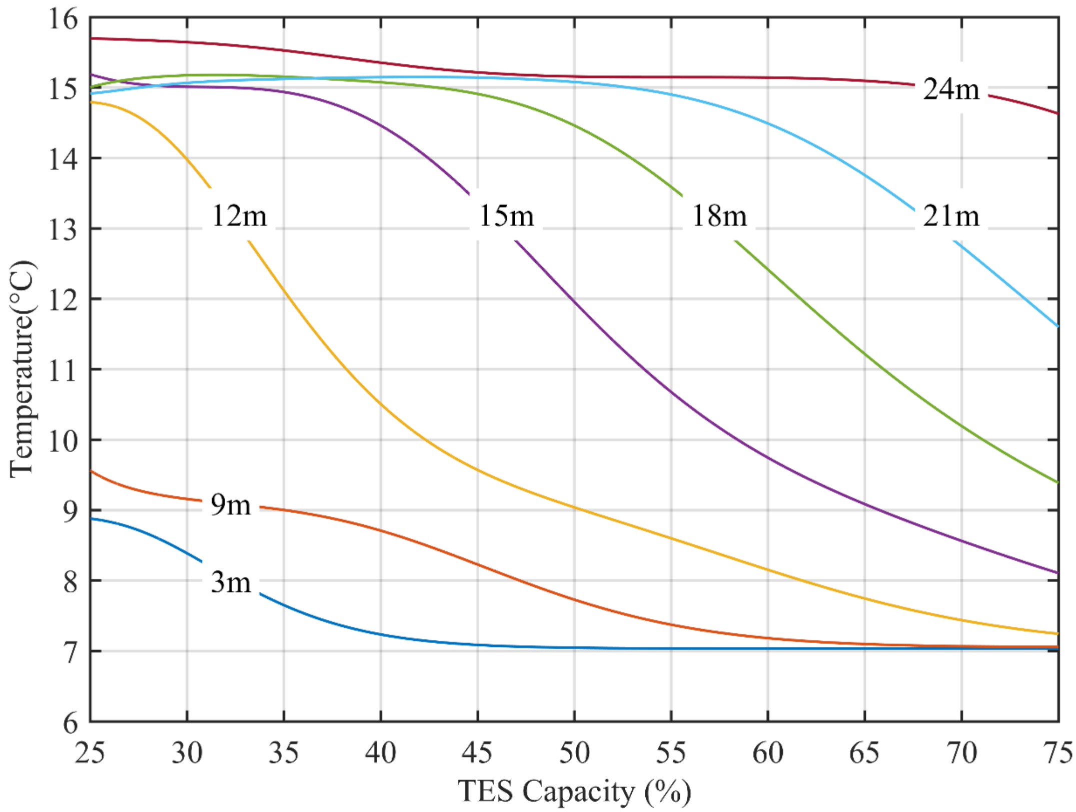

Figure 18: Charging temperatures in the TRNSYS model

While the Richardson number indicated that the inlet has no effect on the stratification, the model stratification occurs over the entire height in the TES during charging. While the differences are present, the influence of the diffusers on the overall TES performance is less significant. As the differences in the temperature profiles are much closer in the discharging cycle.

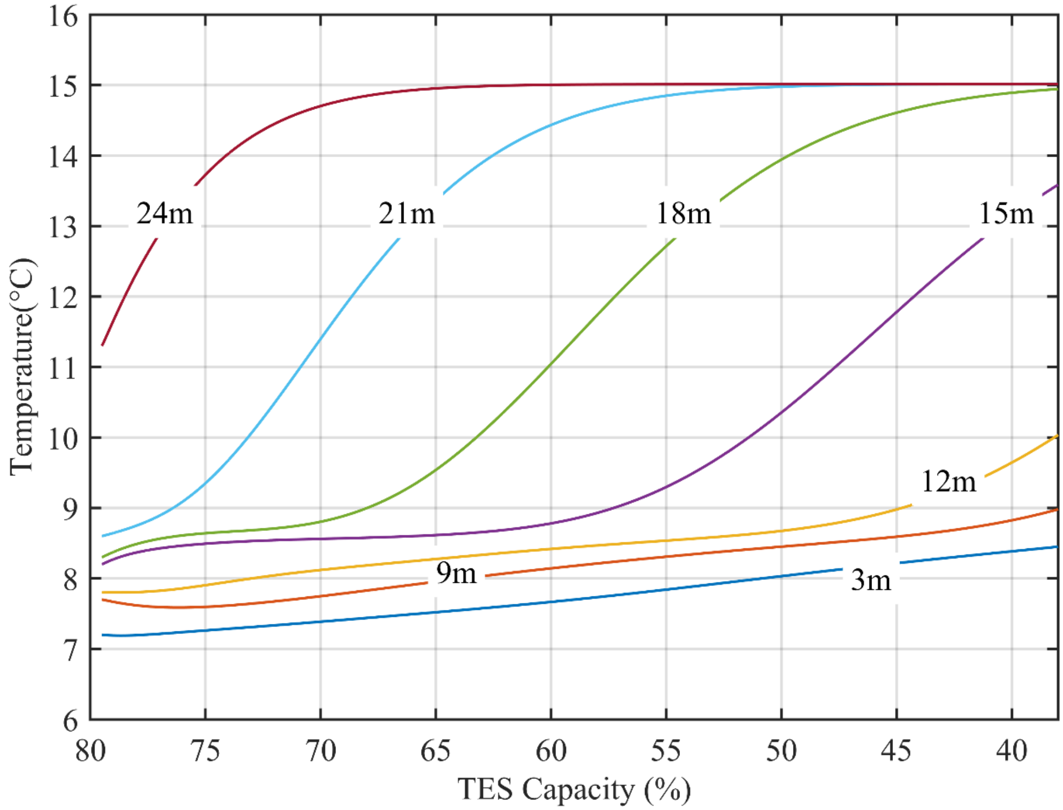

Figure 19: Discharging temperatures in the TRNSYS model

During a discharging cycle shown in Figure 19 initial conditions were setup for the case based upon data obtained from measurements taken. As a result, the TES system starts at 80% rather than at full capacity. The tank is fully discharged in the model, the accompanying figure shows the same capacity range as the actual data for comparison. The differences in the discharging cycle of the TES are more pronounced at the top of the TES where the inlet flow is entering the tank (21 m and 24 m lines). The lower region of the TES where flow is exiting remains very similar to the observed data.

The first purpose of the models was to expand the initial or known data to a full cycle to understand the energy and exergy efficiencies of the TES. Then using that information compare with the results presented in other studies and then expand on the information by evaluation of the individual layer efficiencies and plotting the efficiencies with respect to capacity and time. By evaluation of the model, suggestions for improvement to the existing operating parameters and controls can be made to maximize the efficiency of the TES.

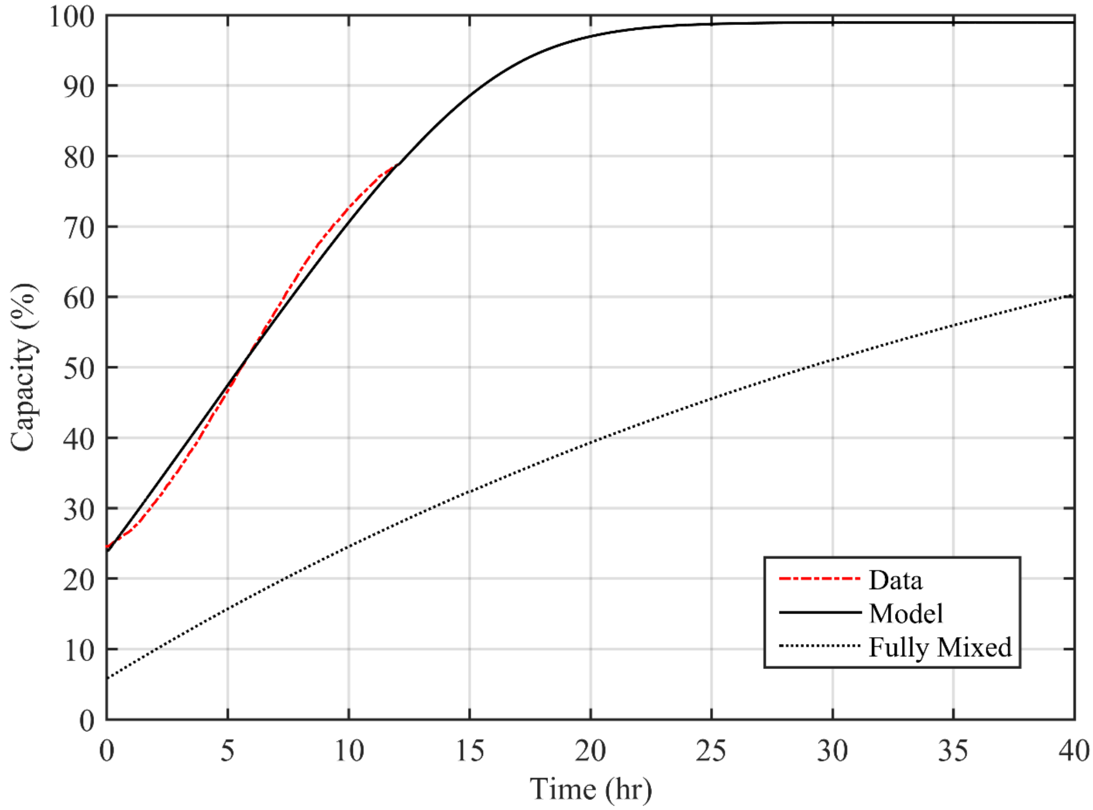

Figure 20: Percent of full cold capacity vs time during a charging cycle and comparison to the measured data and fully mixed model.

Shown in Figure 20 the charging cycle models and data are presented. The capacity is the percent of the full cold storage possible in the TES system. A typical charging cycle that starts at 25% will take 15 hours to reach 90% capacity, at that point the time it takes to increase the cold storage increases. Rather than the 4% per hour below 90%, this process slows to less than 2% change per hour. The differences in the model are reflected by the system dynamics associated with the cooling demand of the actual system. During a typical charging cycle, there is still a significant cooling demand on the campus. As a result, cooling that is produced is shared between the buildings and the TES. Once cooling set points within these buildings are met, the freed up demand is then transferred to the TES until they are needed again at 9 am (after 10-12 hours of charging).

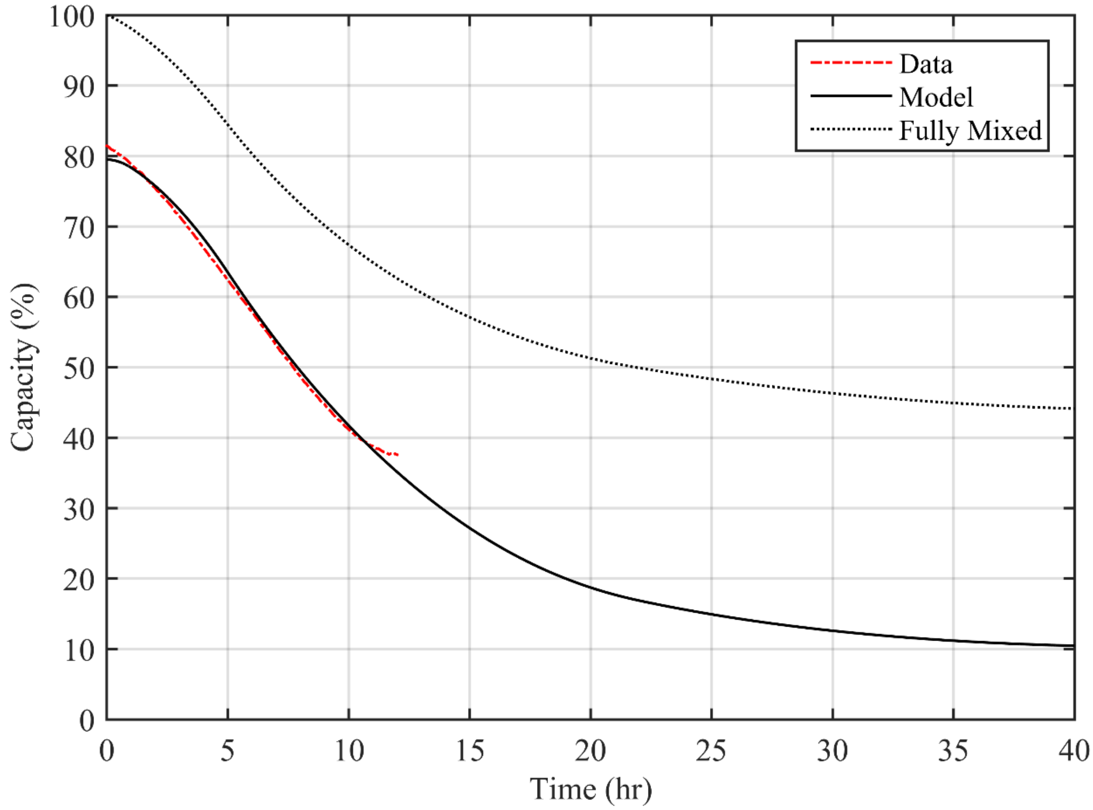

Figure 21: Percent of full cold capacity vs time during a discharging cycle and comparison to the measured data and fully mixed model.

During the discharging model, shown in Figure 21, the TES is setup again with the same initial conditions as the discharge cycle from the data. The model is similar to the capacity change as the data, toward the end of the actual discharge cycle the flow rate is throttled down where the model was designed to fully discharge the TES resulting in differences seen. It can be observed that the capacity change decreases after the 15-hour mark; this is a result of the exiting temperatures increasing relative to the desired temperature. The returning temperature and leaving temperature to become closer and the ability to extract the cooling is much less efficient.

Figure 21 also shows a fully mixed model for comparison. Fully mixed models present a qualitative view into the value of stratified TES systems. At first glance, a fully mixed model would yield better results; on an energy basis this is true, but if the desired output is temperature this is no longer the case. In most situations utilization of TES systems is done so it can be used at a later time. They equipment that uses the energy is often designed with a specific supply temperature. Stratified TES systems maximize the regions of storage at these design temperatures while fully mixed options will continue to change output temperatures as time passes eventually becoming unusable.

4.6 Results and Discussion

By using the model, exergy efficiency calculations can be observed with respect to time and capacity of the TES system can be done in a controlled situation. Observations of the exergy efficiency with respect to time for the charging process are shown in Figure 22, it can be seen that the highest efficiencies of the TES occur during the first 7 hours. By showing the 4 sections of the TES it can be observed that the layers with the highest exergy efficiency are in the top and upper middle sections of the TES. This is a result of the fact that the internal exergy change in these sections are significantly higher than in lower sections that have much less temperature change.

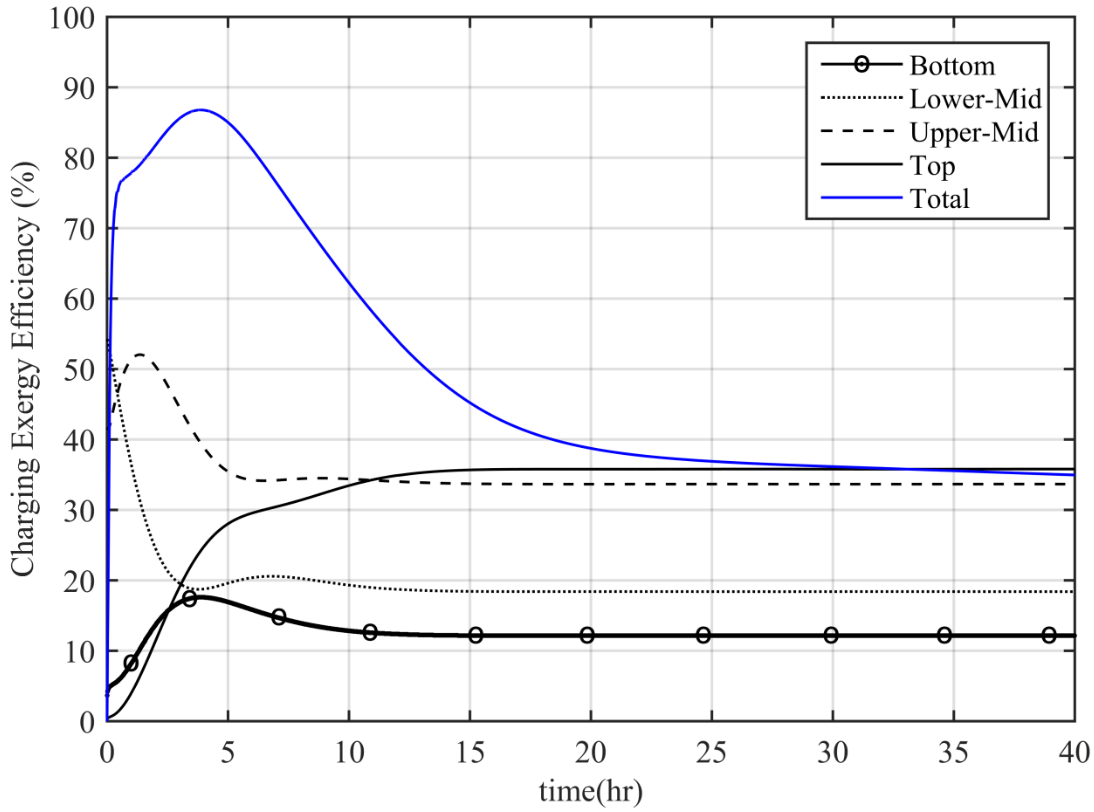

Figure 22: Charging exergy efficiencies of the total TES and 4 sections of the TES vs time.

It is depicted that the bottom and the lower middle sections of the TES system have a lower efficiency throughout the charging process, even after 40 hours. The overall efficiency of the TES after the typical charging time of 12 hours is expected to be 55%. By analyzing the exergy efficiency of the TES during charging indicates that to maximize exergy efficiency charging the TES system for 4 to 5 hours would yield the highest efficiency. By comparing the exergy efficiency with respect to capacity, shown in Figure 23, it can be concluded that as charging the TES passes 42% maximum capacity the exergy efficiency decreases, this is a direct result of the temperature difference within the TES decreasing and the maximum temperature begins approaching the minimum temperature.

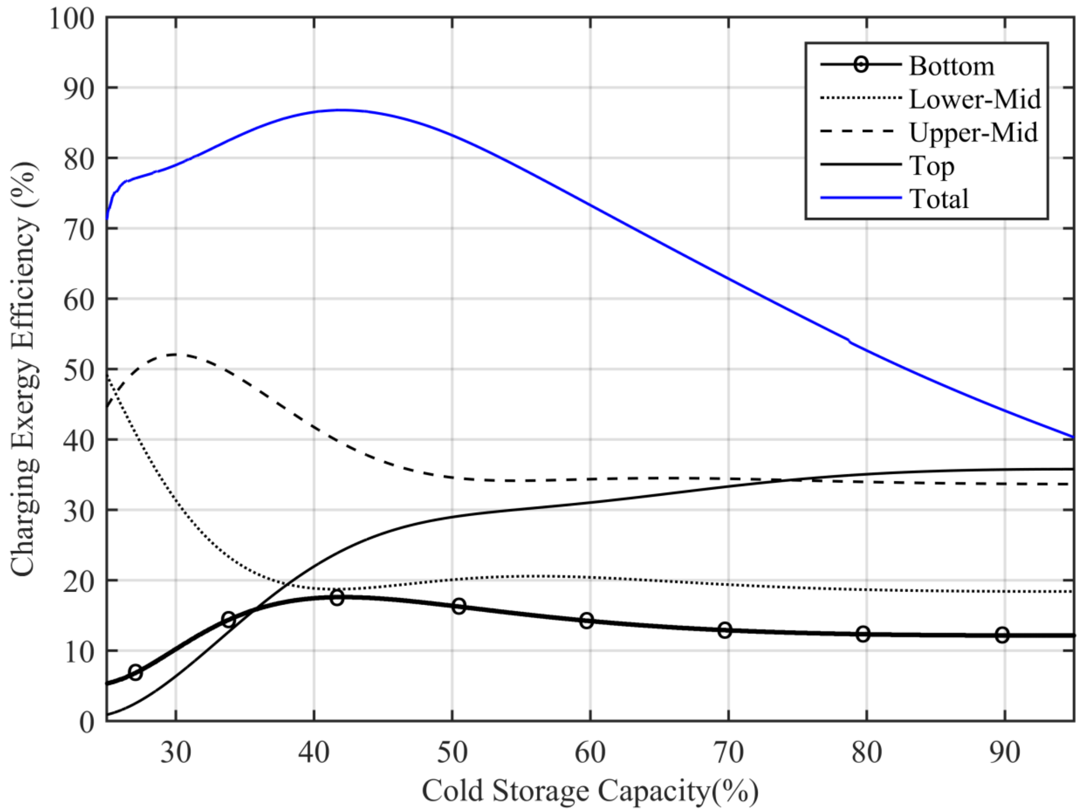

Figure 23: Charging exergy efficiencies of the total TES and 4 sections of the TES vs capacity.

By observation it is clear that charging the TES tank to 40 to 45% capacity will yield the highest exergy efficiency, this is a result of the stratification within the TES as well as the overall temperature difference between the top and bottom. This would be a problem as the intended function of the TES is to offset peak loads during the warmest parts of the day. This deficit would have to be made up by chillers that will then have to operate during the low efficient high-temperature parts of the day. As a result, it can be concluded that charging the TES as to meet the needs of the next day without excessively charging the system would yield the best results.

By plotting the exergy efficiency of a discharging process additional information can be observed with respect to how much of the TES system should be utilized to maximize exergy efficiency. Shown in Figure 24, the exergy efficiency of during a discharge cycle is shown with respect to time. The overall or total exergy efficiency reaches its maximum at around 17 hours where stratification is highest. The various layers show that top and upper middle sections have the highest efficiencies, while the lower middle and bottom sections produce the lowest efficiencies. The temperature difference and the impact of stratification effects the top layer first, increasing its efficiency; as the TES continues discharging, the lower layers follow this process at a reduced effectiveness that results from mixing. It can also be observed that after 30 hours of usage the efficiencies of the layers converge to 22-26%.

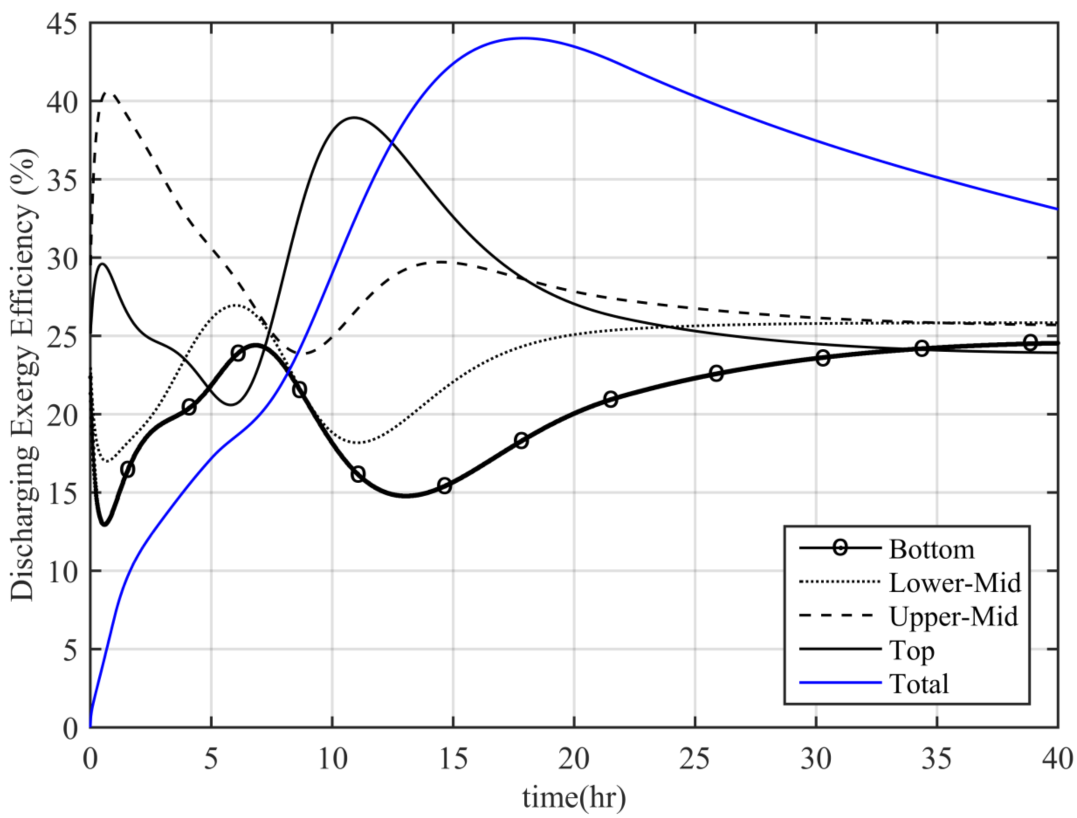

Figure 24: Discharging exergy efficiencies of the total TES and 4 sections of the TES vs time.

By looking at the efficiencies of the layers the top reaches its maximum efficiency at the 10 to 12-hour point. It can be concluded that to maximize the efficiency of the TES system discharging the TES for 15 hours or longer would yield the best results. This is not practical, as the cooling demand required from the TES is not available after 12 hours and a charging cycle must also begin to meet the needs of the next day.

When comparing the exergy efficiency to capacity as shown in Figure 25 additional insight can be obtained. The maximum exergy efficiency of the TES system occurs during a discharge cycle when the process is stopped at 23% of the remaining storage capacity. This is expected as the significant decrease in efficiency following this process is a result of inversion mixing that is beginning to propagate throughout the TES.

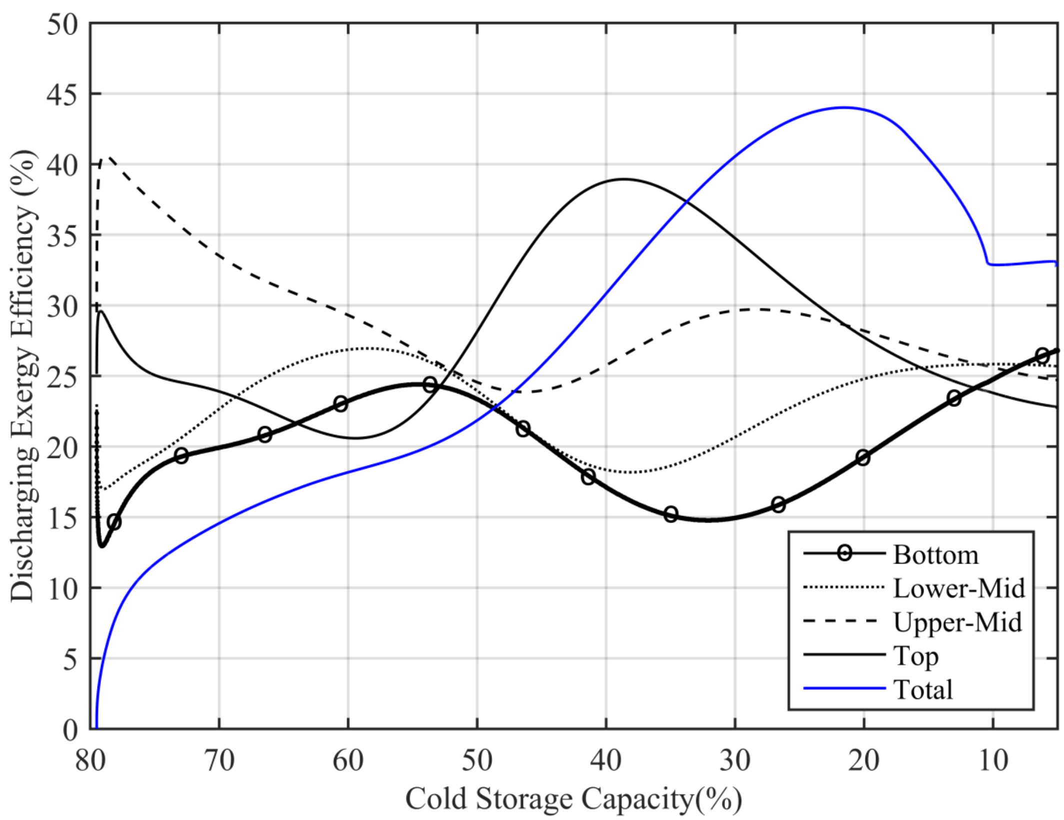

Figure 25: Discharging exergy efficiencies of the total TES and 4 sections of the TES vs capacity.

Comparison of the layers shows that the top and upper middle sections again yield the highest exergy efficiencies for most of the discharging process. The lower middle and bottom sections have their lowest efficiencies just prior to the maximum overall efficiency. Overall it can be concluded that the current operation of the TES system at the University of Idaho results in an overall energy efficiency of 75% with an overall exergy of 20%.

4.7 Validation

In order to validate the model additional comparisons were made. By using the same model and applying the same analysis to the data obtained during winter the second point of analysis can be done. Figure 26 shows the comparative evaluation of the second data set and the results in TRNSYS.

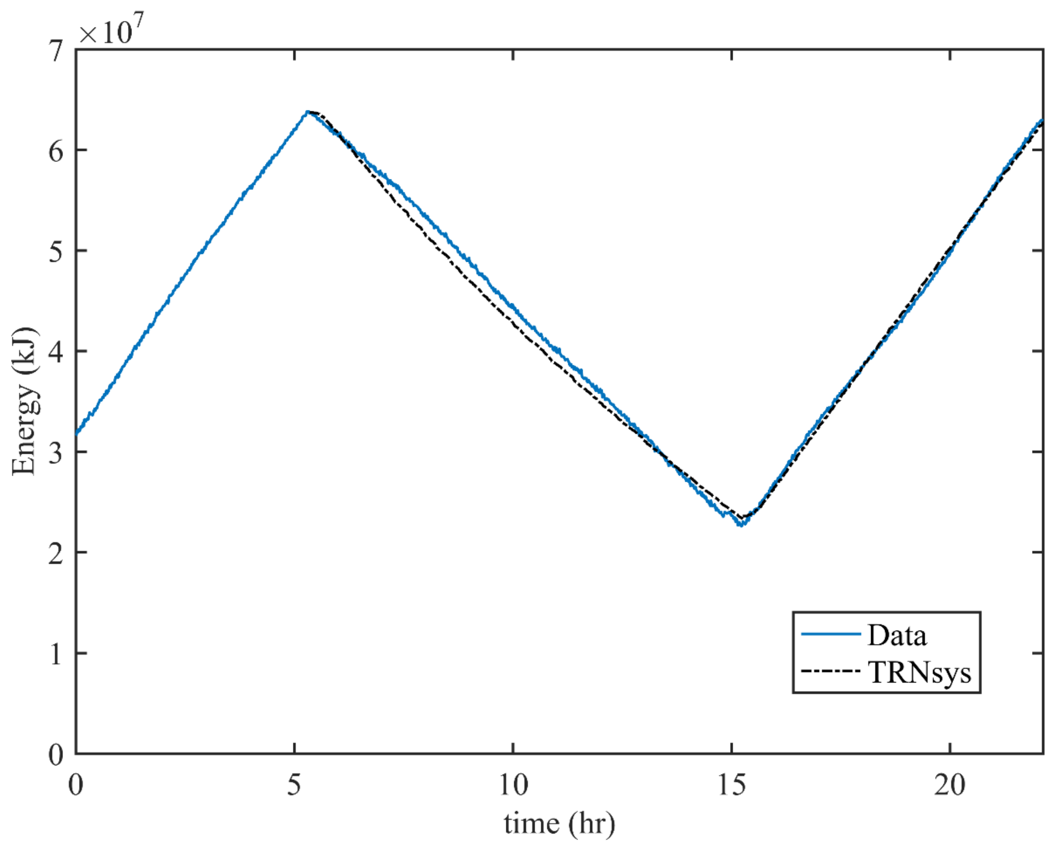

Figure 26: Winter comparison analysis

The data set begins during a charging cycle, and at 5 hours the discharge cycle begins, at this point, the differences in the model are a result of the heat transfer at the walls of the TES. During this data set, the outdoor temperature is less than 7°C resulting in an additional storage capacity gain that was not predicted in the model as a result of the differences in internal temperature stratification, as shown in Figure 27.

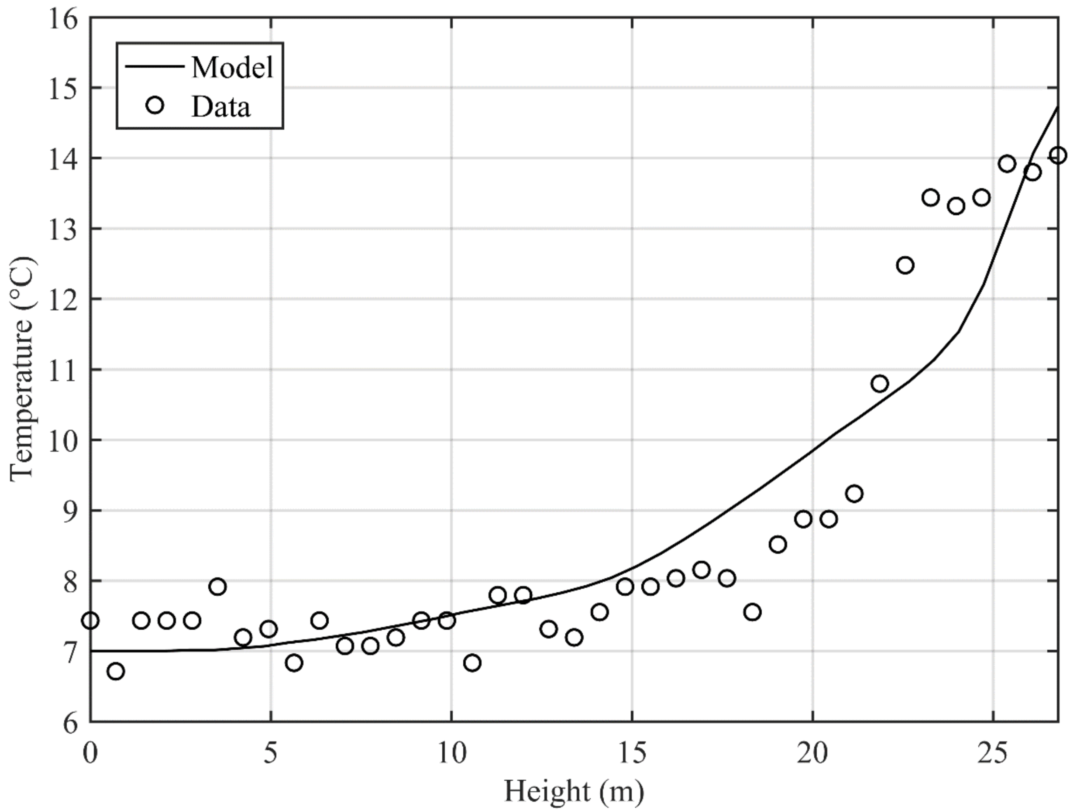

Figure 27: Comparison of stratification between model and data

The differences in the temperatures within the stratification demonstrate the primary cause of the error. The temperature differences in the 22 meter to 25-meter region result in a heat loss to the environment different from what was predicted in the model. The primary cause of temperature profile difference is a direct result of the diffuser stratification interaction that is not represented in the model. Overall, the model and data present differences which are not as significant.

When comparing the total TES system for a discharging and charging cycle it can be shown in Table 12. The results are compared to models presented by Rosen et al considered a case with sensible heat storage where the storage fluid was linearly stratified. This is a more ideal case than the TES at UI. Their system was a controlled experiment using a 5 m high by 2 m diameter cylindrical tank. This system imitated environmental conditions that were predictable and measureable. This approach allowed for precise accounting of energy and exergy within the system. They compared cases of sensible heat storage for a linearly stratified storage fluid with those of fully mixed and latent storage systems. The TES system also had a 17^{o}C temperature difference (2 – 19 ^{o}C) between inlet and outlet flows. This corresponds to the better result for energy efficiencies in their study; this is compared to the results of the case presented in this paper, which contained an 8^{o}C temperature difference. The table compares their stratified storage model to the results of this case study.

Table 12: Comparison of energy and exergy analysis of the TES system with Rosen et al [156]

Efficiencies (%)		Rosen et al [156]	Case Study
Energy	Charging	100	92
	Storing	82	N/A
	Discharging	100	81
	Overall	82	75
Exergy	Charging	98	55
	Discharging	24	36
	Overall	20	20

The energy efficiencies of TES systems are high; storage efficiencies are related to heat infiltration that occurs at the walls. As a result of the very short storage time of the TES system, the storage effects of the case study were neglected. The significant differences in the exergy are associated with the analysis of Rosen et al are a result of the impact of the assumptions used in their presentation. Their model did not take into account heat gain during charging and discharging processes resulting in higher charging efficiencies form the case presented. This is a result of the nighttime temperatures observed in this case study always being higher than the internal temperature of the TES. This should result in a heat gain in the system.

The higher discharging efficiency is a result of the piping within campus, during the charging process chilled water must flow across most of the campus before reaching the TES. As a result, the pipes are filled with chilled water at the start of the discharging process yielding a larger available capacity than what is actually contained within the TES system.

The second difference is a result of the mass flow rates; they used controls to produce constant inlet and outlet temperatures. This differed from the case study because the system in use is differential pressure controlled where flow rates are dependent on usage throughout the university campus.

4.8 Conclusion

The University of Idaho is utilizing the TES system since it was installed in 2010. This system has had limited controls originally. The operation has been largely dependent on operator experience, manufacture instruction, and guesswork to improve performance. Using an analysis which is presented here will assist significantly in understanding the dynamics associated with the charging and discharging of the TES system as well as the ideal ranges to operate the TES system when full charging and discharging cycles occur.

Analyzing measured data, the non-dimensional numbers can be a useful tool for assessment of the influences of various parameters. The Richardson number showed that the current TES stratification is impacted very minimally by the inlet flow. The Biot number was significantly large; this indicates that temperature measurements do not need to be obtained from the centerline of the TES as the temperature between the centerline and the wall should be nearly uniform. The Peclet and Fourier numbers show that predictions on the thermal stratification within the TES can be done without significant information; this is very useful when the measurement is not always possible.

Comparison of individual sections of the TES system allows for understanding which layers are more efficient and should be utilized more often to increase overall system performance. Using the analysis presented here, it was determined that the top half of the TES system is more exergy efficient than the lower sections. As a result developing a usage plan that makes the largest use out of these regions should result in better overall system performance.

Based upon the exergy analysis shown in this study it is recommended that operational changes be made to the current TES system. The maximum exergy efficiency occurs at 43% of the fully charged thermal capacity, the exergy efficiency decreases as the charging process continues. By only charging the TES to meet the demands of the next day the exergy efficiency of the TES will increase. The discharging exergy is shown to increase until 23% capacity, at this point the efficiency significantly decreases. This decrease is directly related to the inversion process internally within the TES and it is recommended to discharge the TES to 25% of the thermal capacity.

By evaluation of the exergy efficiency vs. time users will be able to see where their system should be in operation based upon the time spent charging and discharging the TES system. By comparison of the exergy efficiency vs capacity of the TES, locating and identifying the optimal operating ranges that can be implemented. Utilization of feedback control systems offers the option to farther fine tune this process and make real time adjustments to the TES in an effort to improve exergy efficiency.

TES is the component that makes the energy system more efficient, however, the performance of the TES by itself can be assessed for better performance. There are many opportunities to improve the design and performance of TES. TRNSYS modeling and exergy analysis are some methods for modifying the TES which were explored in this study.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

The comprehensive study of district energy systems including topics of history, identification of systems, energy sources, policy, design, environment, economy, efficiency, performance, advantages, and disadvantages is done. The review shows that encouraging polices, developing tools and creating strategies for reducing dependency on fossil fuels are necessary for approaching a sustainable energy future. District energy systems are the new focus of many aspects of energy management in building sectors. These aspects will provide opportunities for engineers in different fields, economists, investors, and policy writers.

Reducing exergy destruction rates result in improvements to sustainability, occasionally the adjustments to these systems requires little to no physical hardware changes. Data collected was utilized by the model to predict low cost improvements of the absorption chiller at the University of Idaho campus. By increasing the lithium-bromide concentration in small increments within an absorption chiller a net decrease in exergy destruction rates are available.

An inclusive assessment of the exergy efficiency of the TES showed that fully charging the TES resulted in lower overall efficiency of the system. Individual layer of the TES (stratification) comparisons were also conducted to show that upper half of the TES was more efficient than the lower half as a direct result of the stratification and associated temperatures. Efforts to utilize the most efficient regions of the TES should be made while limiting the decrease in exergy efficiency throughout the charging process.

5.2 Recommendations

In order to improve the future use of District energy systems there are many options. It is recommended that using policies to encourage availability and quality of district energy systems through research and financial incentives. Furthermore, these policies also offer means to shift the primary energy sources of district heating and cooling to sustainable options in environments such as renewable energy.

While the model presented is unique to the UI campus absorption chiller, the significance of obtaining the optimal range of any absorption chiller would yield insight unique to that chiller. Each model would be useful for monitoring and predicting practical operating parameters. It is recommended that optimizing the concentration of lithium-bromide within the absorption chiller at the UI Moscow campus is done. Care should be when making small incremental changes the concentrations as any change will result in impacts on the whole chilled water and steam system. Additional consideration should be given to the changes on the pumping costs associated with these results.

By using information obtained from the analysis and modeling of the TES, it is recommended that the TES equipment be operated fully by an automated control system. This system should allow for the feedback control to farther fine tune this process and make real time adjustments to the TES in an effort to improve exergy efficiency.

5.3 Recommendations for Future Work

Further research in the field of district energy should be focused on the technologies and policies necessary to transition from single user systems to district based systems. Development of policies and practices should reflect energy sources as well as the equipment that utilizes renewable resources over conventional fossil fuels. The conversion of single user systems will require policies as well as incentives to encourage long-term investment. Farther research in the policies and incentives necessary to make the transition possible should be considered.

There are substantial research opportunities for studying an entire chilled water system at the University of Idaho Moscow campus. Many of the presented recommendations will impact other systems outside of the scope of this thesis. Future work should take a look at the whole system at a more comprehensive level. This study should include the chillers as well as piping and pumping. Additionally the dynamic behavior of these systems as a result of daily thermal loads should also be addressed.

Additional research is also suggested for the TES system. During the study it was discovered that the stratification within the TES differs from conventional system models. This is most likely a result of the dampers and farther research on this topic should include a comparison of the influence of dampers on the mixing and layer efficiency. It is recommended that a computational fluid dynamics software be used to visually show the influence of these dampers on entering and exiting flow conditions.

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