The Pennsylvania State University

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OPTIMIZED DESIGN OF WATERSIDE ECONOMIZERS FOR LIQUID-COOLED DATA CENTERS

A Thesis in

Architectural Engineering

by

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ABSTRACT

Due to increasing computing demands, the number of data centers and the power density of data centers are continuing to grow. The increase in computing demands emphasizes the need for efficient cooling solutions in data centers. One efficient cooling solution would be to implement a waterside economizer, paired with a liquid-cooled data center. A liquid-cooled data center can provide high-density cooling to the increased heat output from the increased computing demands. Additionally, a liquid-cooled data center typically requires a high chilled water supply setpoint which allows for a significant number of free-cooling hours from waterside economizing.

Current guidance on waterside economizer design does not account for the unique conditions required for a data center. This paper evaluates the design approach of waterside economizers in liquid-cooled data centers to include the cooling tower size, cooling tower range, and heat exchanger size. A parametric study of a liquid-cooled data center with a waterside economizer was performed using EnergyPlus for a total of five US locations with different wet-bulb profiles. Energy and life cycle costs (LCC) from the parametric study were analyzed.

Analysis of the LCC shows that increasing the size of waterside economizer components—consisting of the heat exchanger and the cooling tower—can significantly reduce energy use and operating cost. Additionally, a method was derived from the energy analysis to predict waterside economizer performance based on a location's wet-bulb degree days (WBDD). Lastly, pairing a waterside economizer with liquid-cooled ITE can eliminate full mechanical cooling mode in less humid locations which allows for a more cost-efficient design of waterside economizer chiller plants.

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Chapter 1

Introduction

Data centers are energy intensive buildings that account for around one percent of global energy use (Masanet et al., 2020). Currently, about half of the energy use in data centers is used by information technology equipment (ITE) and the other half is used mostly for mechanical cooling (Cho & Kim, 2016). Global data center energy use has doubled over the past decade and the energy use is expected to triple, or quadruple, over the next decade (Masanet et al., 2020). As data center energy increases, so will the total cooling requirement. Increasing the efficiency of mechanical cooling will help to reduce the rate of increase in energy use for cooling. Therefore, it is crucial to investigate energy saving technologies for mechanical cooling, in data centers, to limit increases in future energy use.

The most commonly used process for cooling ITE uses a computer room air conditioner (CRAC) to pass cold air over the ITE which then absorbs the heat produced from computing (Ni & Bai, 2017). This is also known as air-cooling because air is the medium that directly absorbs the heats before the heat is rejected. Air-cooled data centers are commonly paired with an airside economizer. Airside economizing is a popular energy saving technique for air-cooled ITE. When at the right conditions, an airside economizer brings in outdoor air to directly cool and remove the heat from the ITE, significantly reducing data center energy consumption. However, airside economizers are not without shortcomings. These shortcomings include a large distribution system size (due to the low heat capacity of air), possible particulate or gaseous contamination, and poor humidity control.

Another dilemma with air-cooling is the challenge of setting an appropriate supply air temperature for both the machines and people. Simply put, the conditions for human thermal comfort do not always match the optimal environmental conditions for ITE performance. Optimal computing conditions for ITE come from manufacturers who provide an environmental class that determines a data center envelope's humidity and temperature minimums and maximums. For example, ITE class A1—the most restrictive air-cooling class—has a temperature range from 15-32° C (59° – 89.6° F), as shown in Figure 1-1 (ASHRAE TC 9.9, 2015).

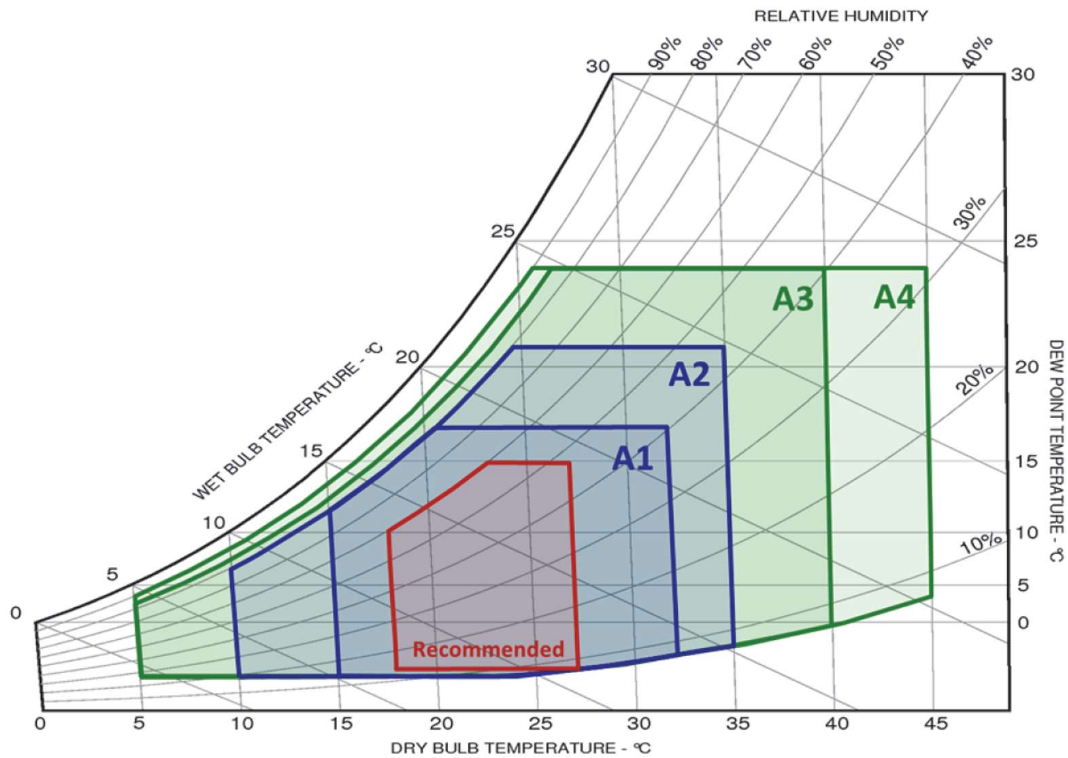


Figure 1-1: 2015 allowable envelope conditions for ASHRAE classes (ASHRAE TC 9.9, 2015)

When cooling equipment in class A1, a data center's mechanical cooling equipment is most efficient when the setpoint is equal to the maximum supply temperature of 32° C. However, this high setpoint is rarely utilized in air-cooled data centers. The first reason that this setpoint is rarely utilized is because this setpoint exceeds the higher limit for human thermal comfort. This setpoint would be uncomfortable to anyone servicing the ITE or working in the same floorspace. Another reason for not using a higher setpoint is the x-factor. The x-factor comes from ASHRAE's *Thermal Guidelines for Data Processing Environments* (2015) which quantifies the chance of failure at different thermal operating conditions, in reference to a 20° C (68° F) operating condition. The x-factor data shows that the amount of ITE failures increase as the dry-bulb setpoint temperature rises (ASHRAE TC 9.9, 2015). Conversely, it was found that data centers can raise the operating points without substantially affecting the ITE reliability (Kelley et al., 2012).

As computing power density continues to increase, and the dilemma continues over the air-cooled setpoint, there has been a shift towards liquid-cooling. Liquid-cooling in data centers is where a liquid directly removes heat from the ITE. The higher heat capacity of liquids, when compared to air, can compensate for the elevated heat output of increased computing. Additionally, liquid-cooling allows for the decoupling of the room and the ITE setpoints. This is because the room air temperature setpoint no longer has to align with the ITE cooling setpoint. This decoupling practice creates a comfortable environment for people and it creates a reliable and efficient environment for the equipment.

Just as air-cooled data centers use airside economizing, liquid-cooled data centers can use waterside economizing to save on energy costs. A waterside economizer, using an open cooling tower, leverages the outdoor ambient wet-bulb air temperature to cool condenser water enough so that the requirement for mechanical cooling is reduced or eliminated by using it to cool chilled water. When a waterside economizer is paired with liquid-cooling technologies, the synergistic effect creates a system that reduces energy use, reduces the probability of failure (by isolating ITE from unwanted air contamination), and supports higher equipment densities.

This research explores the energy and cost benefits of using waterside economizers in a liquid-cooled data center. A computer simulated parametric study was completed for a medium-sized, high power density, data center in a variety of environmental conditions. The results were used to optimize the design parameters of waterside economizers. This research is intended both to be useful for future researchers and to assist practitioners with energy efficient and cost-effective designs.

Chapter 2

Literature Review

This literature review is split into three parts. First, a review will be completed on water-cooled data centers. Next, a detailed look at waterside economizer design, configurations, and controls will be performed. Lastly, current research of waterside economizers in data centers will be summarized.

2.1 Data Centers

Current trends of data centers show an increase in power density as shown in Figure 2-1. To meet these new high density power requirements, liquid-cooling solutions are being implemented (ASHRAE TC 9.9, 2015). There are two different types of liquid-cooling. The first is an immersion system. In an immersion system, the hardware is submerged into a dielectric fluid bath. As the liquid heats up, it evaporates. Then the vapor is cooled until it condenses and returns to the fluid bath to aid in cooling again. The second type of liquid-cooling system is direct-to-chip cooling in which liquid is supplied only to the hardware components that require heat removal (e.g., processor).

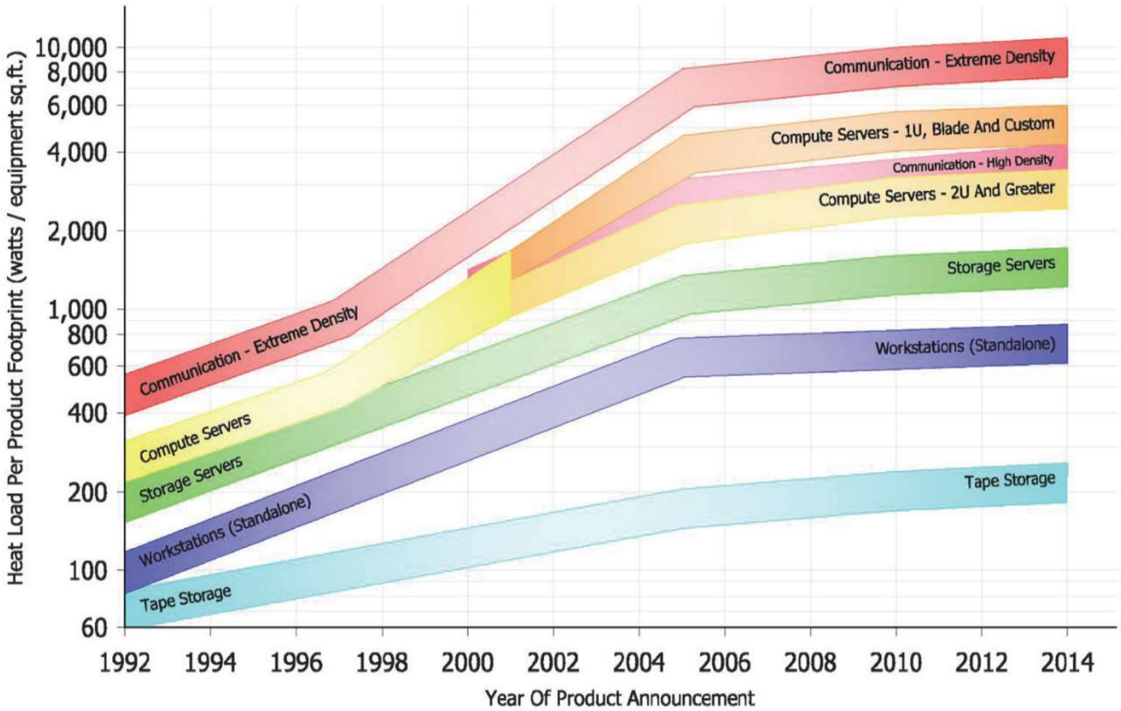


Figure 2-1: Heat density trends for ITE products (ASHRAE TC 9.9, 2015)

ASHRAE (2019) has divided environmental conditions, for water-cooled equipment, into five different classes ranging from W1 (most restrictive) to W5 (least restrictive) as shown in Table 2-1. In general, the lower the liquid-cooling class, the lower the supply temperature required. Equipment classes W3, W4, and W5 require little to no mechanical cooling. It is possible to set up a data center with less restrictive ITE in classes W3 to W5, however, the lack of availability of these ITE equipment classes makes this option rarely possible (ASHRAE, 2019).

Table 2-1: Liquid-cooled datacom facility classes (ASHRAE, 2019)

Class	Facility Supply Water Temperature (°C)
W1	2-17
W2	2-27
W3	2-32
W4	2-45
W5	>45

The basic configuration of a water-cooled data center is shown below in Figure 2-2. A chilled water loop supplies cooling water to a cooling distribution unit (CDU). The CDU provides strict temperature control to a group of ITE. Outside of the CDU, the chilled water system is very similar to a conventional system with the exclusion of the chilled water supply setpoint. Figure 2-2, below, shows the cooling water temperature requirements for common liquid-cooled equipment. The relatively high temperature of the supply water, compared to comfort cooling applications, makes a data center an attractive option for a waterside economizer.

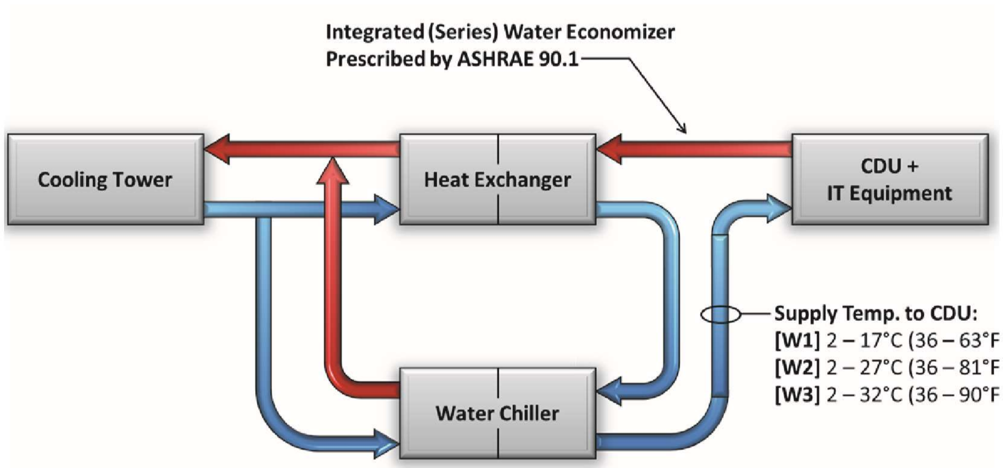


Figure 2-2: Liquid-cooled guidelines for data center classes (ASHRAE TC 9.9, 2015)

Figure 2-3 shows the water-cooled server trends over several years. This diagram shows the maximum facility supply temperature along with the server footprint. It also compares the footprint if the server was either air cooled or indirectly cooled. Indirect cooling is where the heat is absorbed through an air-to-water heat exchanger before the ITE. Out of the twenty-eight products released, a total thirteen of the products were very close to or within class W1 (ASHRAE TC 9.9, 2019).

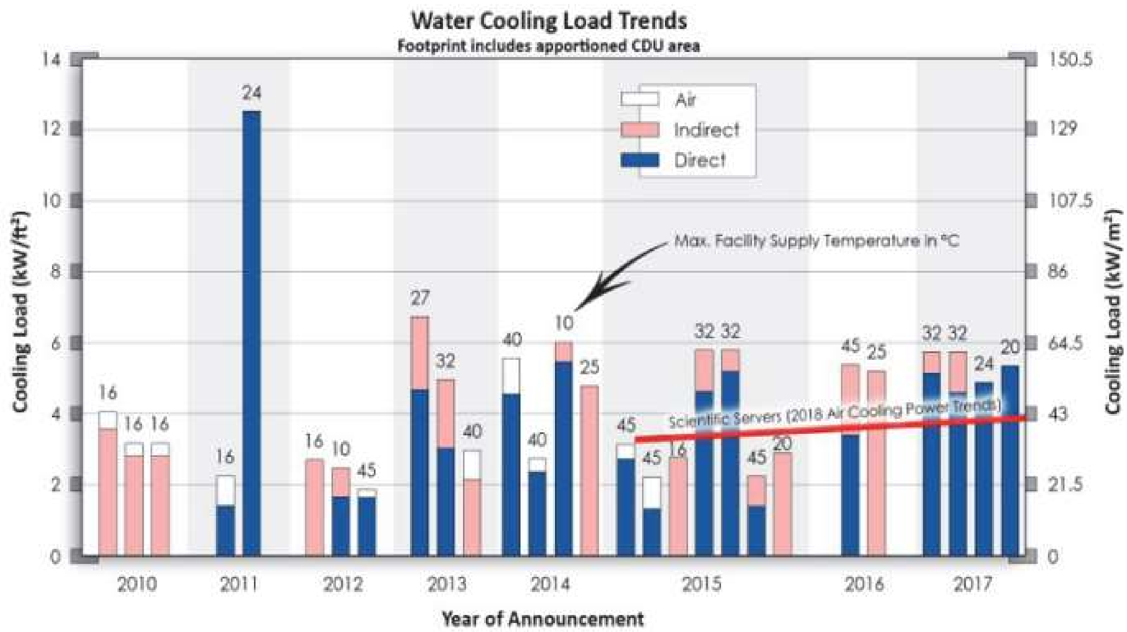


Figure 2-3: Water cooling trends (ASHRAE TC 9.9, 2019)

2.2 Design, Configuration and Control of Waterside Economizers

2.2.1 Design

This section of the literature review summarizes current guidance on designing waterside economizers. A waterside economizer is a subsystem that allows cooling towers to cool the chilled water loop directly when conditions are favorable, thereby reducing or eliminating the requirement for mechanical cooling. In order to add waterside economizer capability to a chilled water system, only a few components need to be added or modified. The main component that needs to be modified is the cooling tower. Normally, a cooling tower is sized for the largest chiller heat rejection load during the summer. However, when sizing a cooling tower for waterside economizer duty, a winter design condition will have to be evaluated, in addition to a summer design, where the cooling tower handles 100 percent of the load without mechanical cooling (Beaty et al., 2018). For buildings that fall under ASHRAE 90.1, waterside economizing is required to complete 100 percent of the free cooling at 50° F dry-bulb / 45° F wet-bulb and below (ASHRAE 90.1, 2019). Data centers do not fall under ASHRAE 90.1, and thus the appropriate winter design condition will depend on the data center's equipment class and the location's wet-bulb attributes. The winter and summer cooling tower design conditions will be compared and then the cooling tower with the higher required capacity will determine the final design of the cooling tower. It is likely that the winter cooling tower design conditions will require a larger cooling tower because of the characteristics of how a cooling tower operates at lower wet-bulbs. For example, an open circuit cooling tower with an approach of 7° F at 78° F wet-bulb will have an approach of about 19° F at 35° F wet-bulb for the same range (Beaty et al., 2018). In order to provide the condenser supply temperature required for 100 percent economizing, the size or quantity of the cooling towers must be increased to offset the increased approach during winter. It is important to note that increasing the size of the cooling tower, to meet the winter load, will increase the efficiency of the system even when the economizer is off (Beaty et al, 2018; Taylor, 2014). This increased efficiency is a result of lowered condenser water temperatures with the larger cooling towers. Moreover, a data center is a mission critical facility, and it will have a minimum of one spare (N+1) cooling towers for redundancy. Economizer operation is often considered non-mission critical, therefore an alternate design and selection method for the cooling tower would be to size the additional cooling tower to make up the difference between the summer and winter load (Beaty et al, 2018).

The main component that needs to be added to enable waterside economizer operation is a heat exchanger. Although it is possible to directly use the condenser water to cool the coils, it is not encouraged because of the potential for fouling of the chilled water system by the dirty cooling tower water (Bahnfleth & Rehfeldt, 1996). When the system is in free cooling mode, the heat exchanger will cool the return chilled water with condenser water. It is common practice to select a plate and frame heat exchanger with an approach of 3° F (Taylor, 2014; Stein, 2009; Kelly, 1996). This approach could be decreased below 3° F, but it is usually more cost effective to increase the size of the cooling tower rather than increase the size of the heat exchanger (Stein, 2009). A larger cooling tower is more cost effective because the cost of a heat exchanger increases rapidly with decreasing the approach (Stein, 2009). Furthermore, a larger cooling tower will also increase efficiency during non-economizer operation, as discussed above. To achieve a low heat exchanger approach, a gasketed plate and frame heat exchanger is usually chosen because it can provide a lower approach than a shell and tube heat exchanger. A plate and frame heat exchanger works by using several heat transfer plates, with highly turbulent flow between the plates. The high heat transfer surface area, and the turbulent counterflow combine to provide a low approach. An additional benefit of a gasketed plate and frame heat exchanger is that it can be opened which allows it to be cleaned or more plates to be added.

2.2.2 Configuration and Control

Two common plant configurations for waterside economizers are shown in Figure 2-4 below. Figure 2-4A shows a "non-integrated" design where the heat exchanger is placed in parallel with the chiller. A better method is the "integrated" economizer, which is also shown in Figure 2-4B. The integrated design method places the heat exchanger before, and in series, with the chiller on the return side (Stein, 2009). The integrated configuration can pre-cool water entering chillers reducing the load on the chillers and extending economizer hours (Taylor, 2014). This allows the system to run either using all mechanical cooling, all economizer, or using partial economizing mode (economizer pre-cools water entering chillers). When in partial economizing mode, the condenser water cools the return chilled water when the heat exchanger can create at least a 2° F decrease on the return chilled water side (Taylor, 2014; Hanson & Harshaw, 2008).

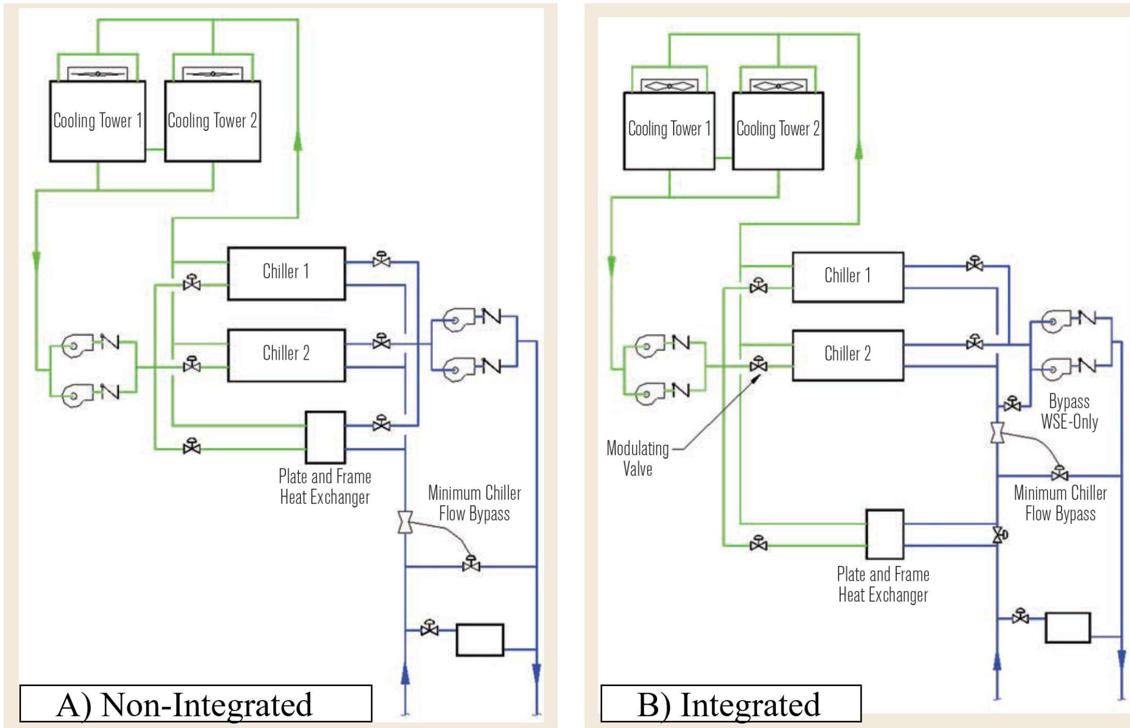


Figure 2-4: Waterside Economizer Configurations (Taylor, 2014)

Chillers have lower limits on the entering condenser water temperature that are higher than the ideal temperatures for economizer operation. Therefore, using a chiller that can accept a low entering water temperature is advantageous when using a waterside economizer (Taylor, 2014). Accepting a low entering temperature will also decrease the lift on the chiller thus improving its efficiency. With low entering water temperatures, either head pressure control or tower bypass control is required so the chiller does not shut down due to a fault condition. For the tower bypass method shown in Figure 2-5A, the heat exchanger is placed to receive the coldest condenser water and the chillers can mix return condenser water with incoming condenser water so entering temperature does not fall below the minimum setpoint (Kelly, 1996). This method allows the chillers to easily maintain the minimum entering temperature while maximizing the effectiveness of the economizer. The head pressure control method, shown in Figure 2-5B, uses a condenser pressure signal from the chiller to modulate water flow rate to maintain the minimum head pressure set point (Kelly, 1996).

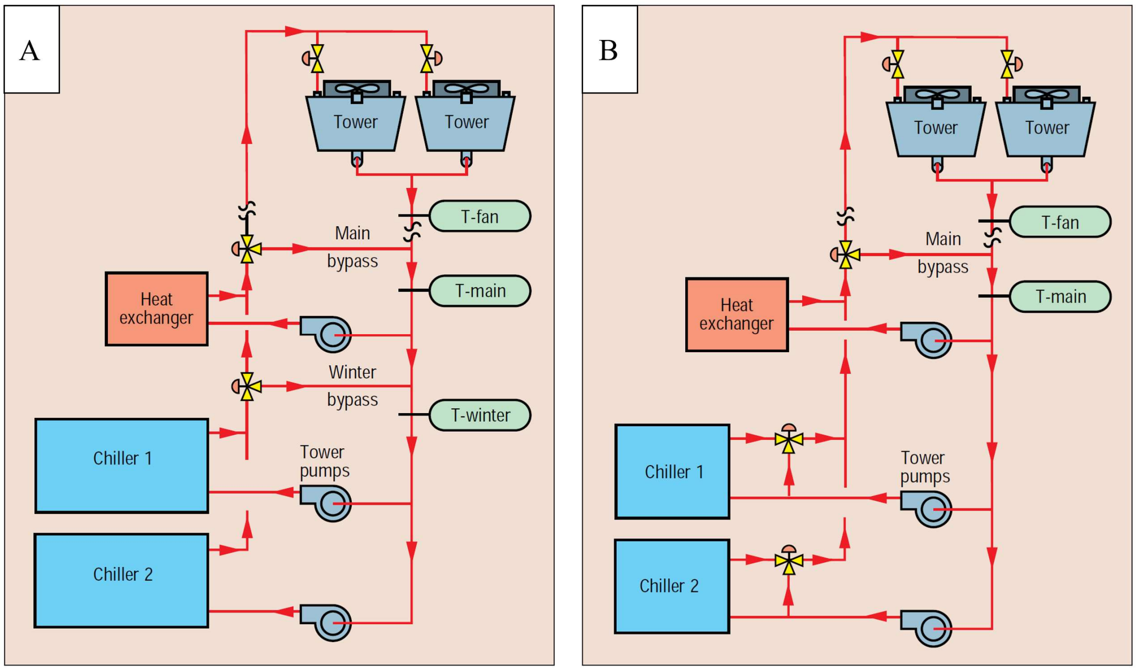


Figure 2-5: Chiller Control: A) Winter Bypass Control B) Heat Pressure Control (Kelly, 1996)

A waterside economizer can be used in both primary-only and primary-secondary chiller plant pumping configurations as shown in Figure 2-6 and Figure 2-7. A primary pumping configuration is one in which there is only one set of pumps, and the bypass is sized for the minimum flow of a chiller. Alternatively, a primary-secondary system typically has one set of constant speed primary pumps for the chillers, and a second set of variable speed pumps for the load. Additionally, the bypass is sized for the maximum flow through a chiller to create two independent pumping circuits. For each of these configurations there is an optimal spot to place the heat exchanger for maximum effectiveness. For a primary-only system, the best place for the heat exchanger is in the primary loop on the return side close to the plant (Kelly, 1996). For the primary-secondary system, the heat exchanger should be located in the secondary loop before the bypass (Kelly, 1996). It should go before the bypass to ensure that none of the chilled bypass water goes through the heat exchanger, dropping the temperature difference in the heat exchanger.

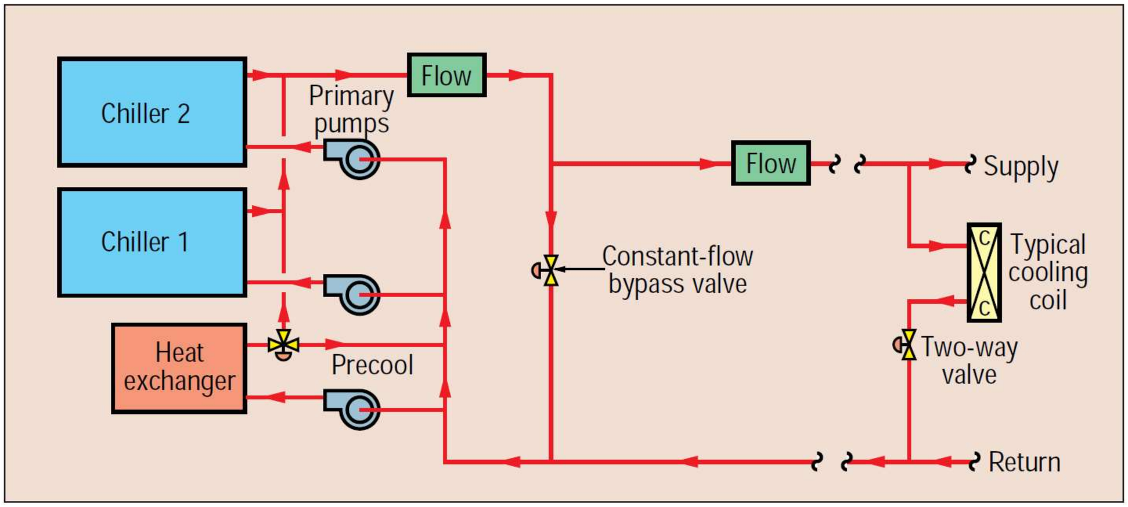


Figure 2-6: Preferred primary-only free cooling heat exchanger location (Kelly, 1996)

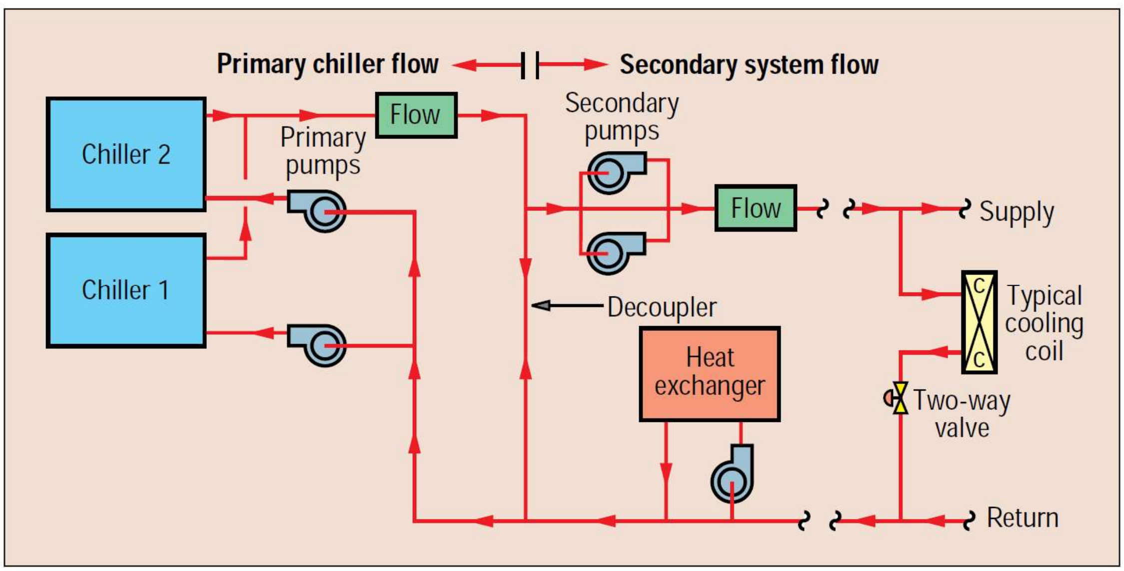


Figure 2-7: Preferred primary-secondary free cooling heat exchanger location (Kelly, 1996)

2.3 Findings: Data Centers and Economizers

One prominent energy saving technique for data centers is airside economizing. An investigation of airside economizer energy performance found thirty percent annual energy savings for a data center in Santa Clara, CA (Alipour, 2013). However, airside economizing is limited by the low heat capacity of air, possible particulate or gaseous contamination, and humidity control. A paper by Beaty et al. (2019), showed the potential for a waterside economizer for different air cooling setpoints. Although this paper showed the potential for increased setpoints, it did not show potential for pairing a waterside economizer with liquid-cooling. The number of hours without the need for mechanical cooling using an airside economizer are below in Table 2-2.

Table 2-2: Waterside economizer hours with no required mechanical cooling (Beaty et al., 2019)

OUTDOOR AIR WET-BULB TEMPERATURE BIN °F	CWS[a] °F	SUPPLY AIR TEMPERATURE[b] °F	PERCENT OF YEAR BELOW WET BULB						
			LOS ANGELES	SAN JOSE	DENVER	CHICAGO	BOSTON	ATLANTA	SEATTLE
59	66	76	61	78	93	74	75	54	90
53	60	70	30	46	78	63	63	42	68
47	54	64	10	21	64	53	52	31	45
41	48	58	2	6	53	44	41	20	21

Published research for waterside economizing is limited and published research for waterside economizing for liquid-cooled data centers is non-existent. The use of a waterside economizer for air-cooled ITE has proven to be a valuable practice. Stein (2009) discusses two projects for which his customers had selected a waterside economizer for their data centers. One had a payback of less than a year and one had a payback of 5-10 years (Stein, 2009). Stein also completed a simulation to estimate the potential energy savings. The results are summarized in Figure 2-8, where even in a warm climate like El Paso, TX, the energy savings were large. There is also some real building data on the potential of waterside economizing in data centers. Out of the seventeen state of the art data centers examined by J. Cho et al. (2016), five utilized waterside economizers.

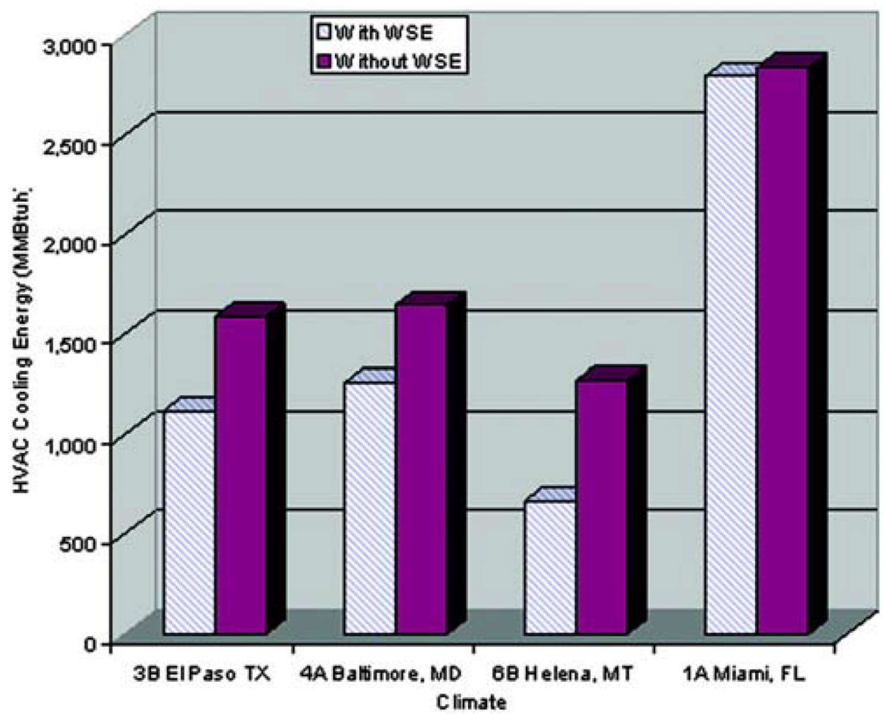
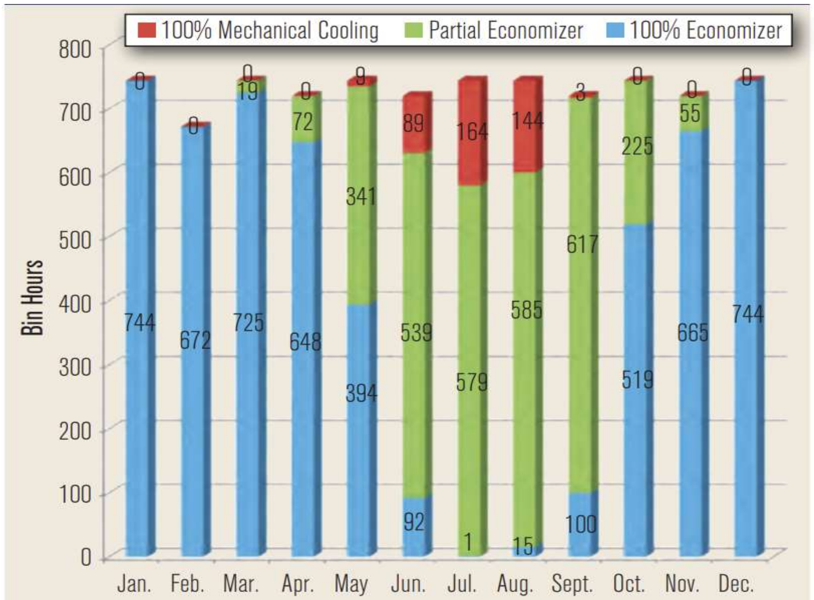


Figure 2-8: Waterside economizer energy savings in four climates (Stein, 2009)

One case study presented the results of using a waterside economizer in Chicago, IL, with a 60° to 63° F chilled water setpoint, allowing for sixty-one percent of annual hours in full economizing and thirty-two percent of annual hours in partial economizing mode (Griffin, 2015). This study also referenced a low approach heat exchanger and oversized cooling towers but did not specifically state what values were used. Additionally, it should be noted this building had air-cooled ITE. An annual snapshot of Griffin's study is shown if Figure 2-9.



CWP OPERATING MODE	ANNUAL HOURS	% OF HOURS
Mechanical Cooling	654	7%
Partial Economizer	2,787	32%
Full Economizer	5,319	61%

Figure 2-9: Bin hours for Chicago’s data center chiller plant operation (Griffin, 2015)

Chapter 3

Research Questions and Objective

Even though use of waterside economizers in data centers has gained widespread application over the past two decades, many aspects of their design have not been explored in literature. A common design parameter is to use waterside economizers where the weather produces at least 3000 hours at, or below, 55° F wet-bulb temperature (PG&E, 2006; VanGeet et al., 2011). Currently, common design guidelines do not provide further recommendations on how to optimize for equipment class or location. The following bullet points describe the research questions this thesis seeks so address.

- Most waterside economizer published literature recommend that a cooling tower should be sized for the winter design conditions. However, literature does not discuss whether further increasing the size of the cooling tower has any benefit for certain locations. This leaves open the question of whether it is possible to further increase the size or number of cooling towers to increase monetary and energy savings. Furthermore, is the optimized size of the cooling tower correlated to a location's annual wet-bulb characteristics?
- As in the case of cooling towers, there are several possible strategies for selecting heat exchangers. Nevertheless, there is no further detail on how to optimize the approach of the heat exchanger. Resultantly, one would like to know whether there is an optimum heat exchanger approach.
- The smaller the range in the condenser, the better the chiller and the waterside economizing mode will perform for a given flow rate, because lower load results in a lower cold-water temperature leaving the tower. Conversely, a lower flow, and higher range, decreases pump energy and makes the condenser water system

less expensive. Is there an optimum condenser water range that will maximize heat transfer while balancing pump energy and plant cost?

This research explores the potential of optimizing the heat exchanger approach, cooling tower range, and cooling tower approach in a liquid-cooled data center. The objective is to relate, and understand, how these design parameters perform in different locations. The overall goal is to improve how waterside economizers are designed.

Chapter 4

Methodology

4.1 Overview

To answer the research questions, and complete the objective, a parametric study was completed. This chapter will outline the methods and assumptions used to complete the parametric study. For the parametric study, a data center and chilled water plant were modeled with, and without, a waterside economizer. The model without a waterside economizer is referred to as the baseline system. The baseline system will be used to compare against the parametric study results. These models were simulated in EnergyPlus, a whole building energy simulation program (DOE, Version 9.2.0, 2019), to find the optimum cooling tower range, cooling tower approach, and the heat exchanger approach.

4.2 Data Center Configuration

The modeled data center was a medium-sized data center with 493 racks and 12,500 SF of compute space (US Chamber of Commerce, 2017). Each rack had a typical liquid-cooled power density of 30 kW per rack, which exceeds the power density that many legacy air cooled racks can handle (ASHRAE TC 9.9, 2015). Multiplying the number of racks by the power density gives a total power of 14,770,000 W (4195 tons) for the data center. This total power represents the cooling load used for the simulations. The cooling load was assumed to be constant throughout the entire year. In a real data center, the design load would be slightly larger to account for other loads (e.g. comfort cooling of the occupants, heat output of other auxiliary equipment, lighting, etc.). The total of all these additional loads will be insignificant when compared to the load of the ITE. The ITE was assumed to operate in liquid class W1 conditions. Class W1 was chosen because most of the products that required liquid-cooling, from Figure 2-3, were within or very close to class W1. Classes W3 and above, with very high chilled water setpoints, do not require mechanical cooling and will not be studied in this paper. Class W2 requires a small amount of mechanical cooling, but because manufacturers are not targeting that class, it will also not be modeled. Therefore, class W1 was chosen to represent a majority of the products that require mechanical cooling.

4.3 Data Center Locations

The data center was simulated in five different locations: Dallas, TX, Chicago, IL, San Jose, CA, Washington, D.C., and Salt Lake City, UT. These locations were chosen because they are common locations for data centers and each location has a distinctly different wet-bulb profile. These wet-bulb profiles are shown, in Figure 4-1, in duration curve form. The duration curve shows the number of hours exceeded for the range of annual wet-bulb temperatures. The higher the curve is, the more humid the environment is, and the worse a waterside economizer is expected to perform. A relatively flat duration curve represents a consistent wet-bulb temperature through many parts of the year. Whereas a curve with a larger slope represents a larger span of experienced wet-bulb conditions. These wet-bulb profiles are the key to predicting waterside economizer performance, as discussed in the results section.

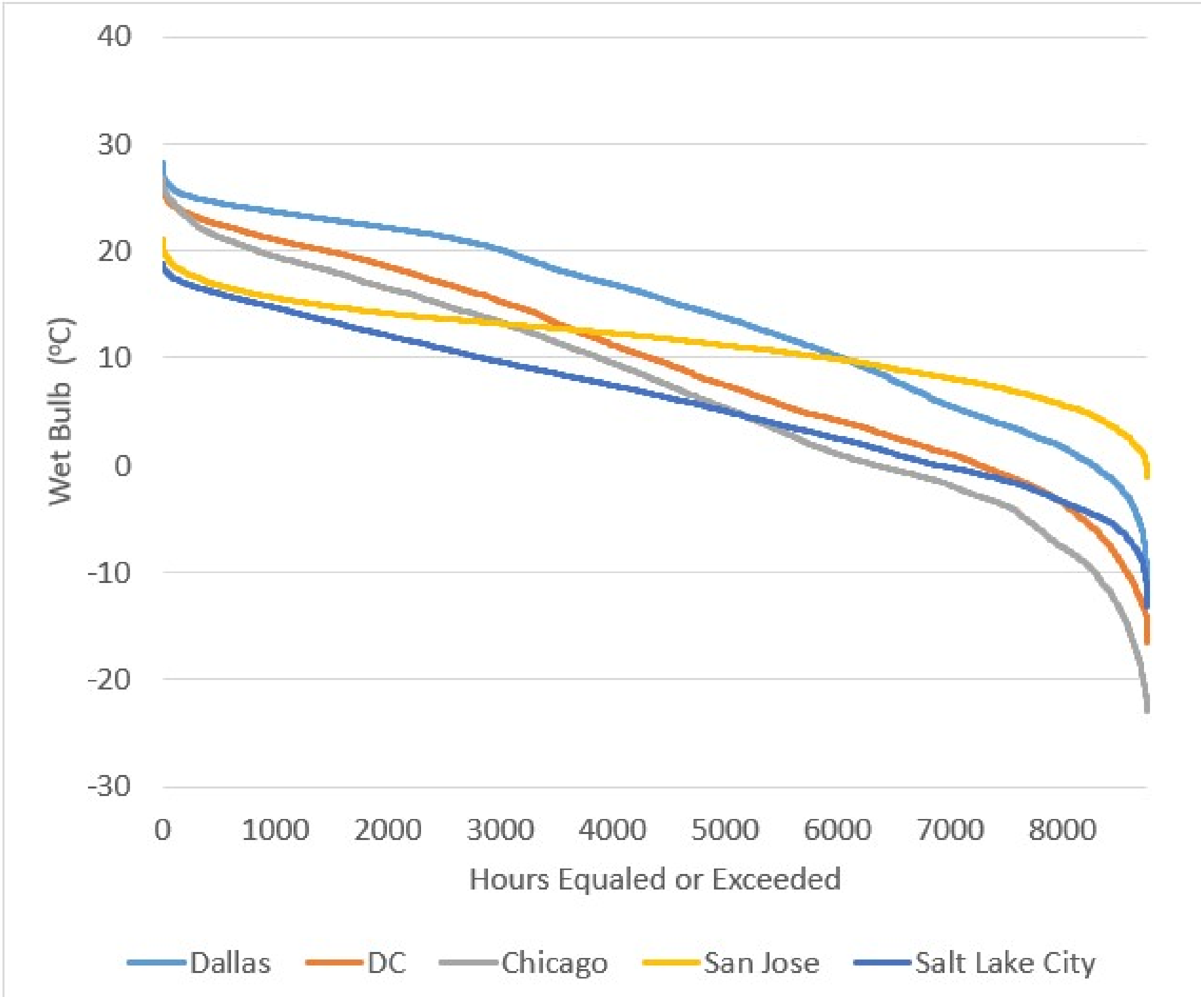


Figure 4-1: Wet-bulb duration curve for the five simulated U.S. locations

4.4 Cooling Equipment Configuration

To cool the data center's ITE, a chilled water plant was modeled as shown in Figure 4-2. The pumping configuration used was variable primary flow as recommended by PG&E's *High Performance Data Centers* (2006) and FEMP's *Best Practices Guide for Energy-Efficient Data Center Design* (2011). The system was configured with three equal-sized constant speed chillers and three variable speed pumps to meet the maximum load. An extra chiller and pump were added into the model for the minimum required redundancy of a data center (N+1). The redundant chiller and pump were allowed to be active during the simulations when the extra component decreased plant energy use.

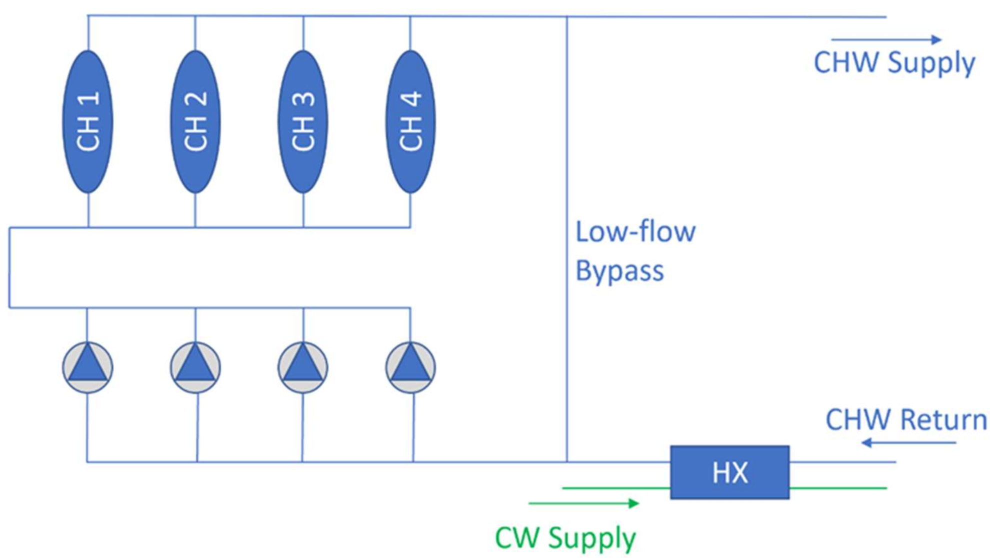


Figure 4-2: Chilled water system model flow diagram

The condenser water system model is displayed in Figure 4-3. It includes three equal-sized cooling towers and three variable speed pumps to handle the design load. Like the chilled water model, one additional component was added to the condenser template for redundancy. A heat exchanger was added in parallel with the chiller's condensers. This heat exchanger is the key component in waterside economizing that transfers heat from the chilled water loop to the condenser water loop.

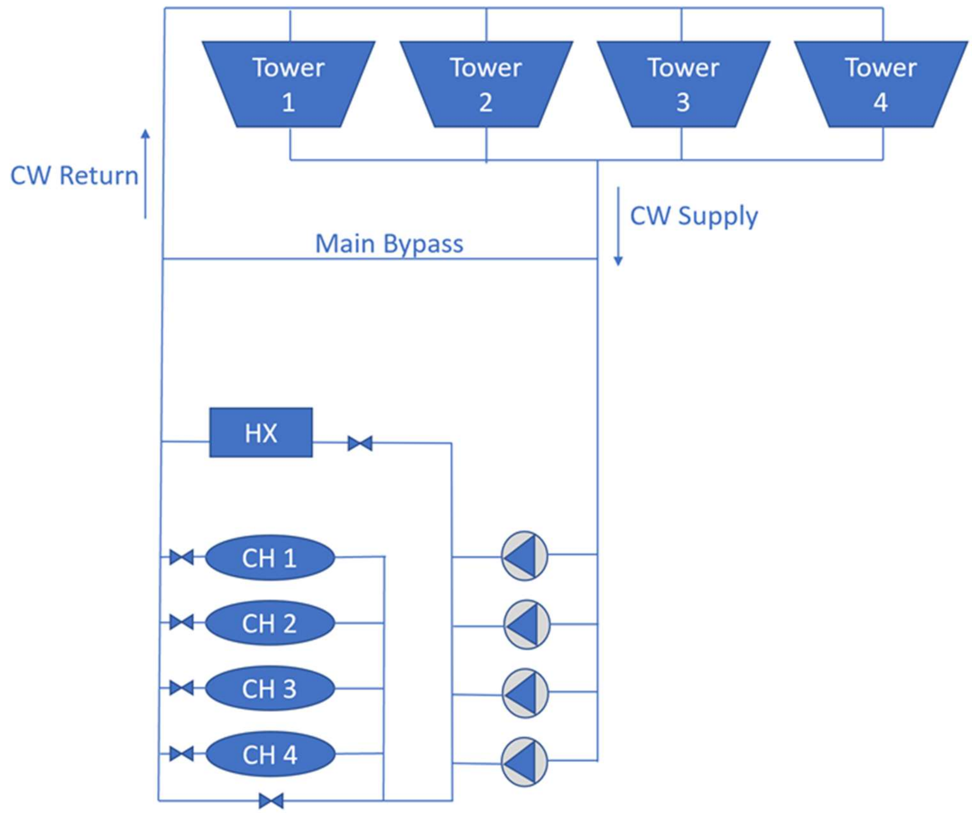


Figure 4-3: Condenser water system model flow diagram

4.5 Program Selection

The parametric study was completed using the programs shown in Figure 4-4. First, Engineering Equations Solver (EES) was used to calculate the design values for each simulation (Klein, 2020). EES has a parametric table function that allows the design process to be easily repeated for each set of design values and locations. Additionally, many thermal properties are built into the software allowing for a more robust calculation. Once the design values were calculated in EES, they were entered into EnergyPlus. EnergyPlus is a whole building energy simulation program with parametric study capabilities (DOE, Version 9.2.0, 2019). EnergyPlus is free to download and is frequently used and trusted by building energy modeling experts.

EnergyPlus was used to perform a quasi-static annual simulation in ten-minute time steps. After the simulations were completed in EnergyPlus, they were opened in DView to verify the controls were working as intended and that the component energy use was as designed. DView is a free software that can easily and quickly plots multiple outputs from EnergyPlus (BEopt, 2020). After the component behavior and values were verified in DView, RStudio was used to analyze the results. RStudio is a free data science and coding environment that allows for easy uploading of various EnergyPlus outputs (RStudio, Version 1.2.5019, 2019). RStudio was used for storing and comparing large amounts of data and plotting results.

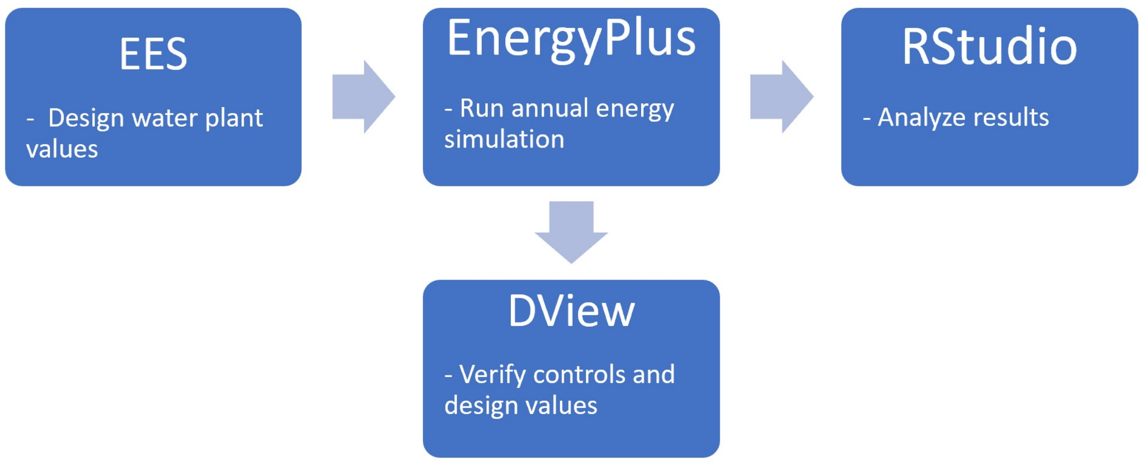


Figure 4-4: Parametric study computational flow chart

4.6 Parametric Design Values Calculations

This section presents the calculations required to do the parametric study. The controlled variables are the cooling tower approach, cooling tower range, and the heat exchanger approach. As the controlled variables changed, so did many other design parameters in the plant. For example, when the design cooling tower range was changed, so the condenser pump and pipe size. Since the majority of these calculations were dependent on one another, all the calculations were all completed in EES for repeatability. In order to complete these calculations, many values were derived from experience, literature, and product specifications. A list of all the parametric values that were calculated and entered in EnergyPlus can be found in Appendix A.

4.6.1 Cooling Tower Design

4.6.1.1 Cooling Tower Range

The cooling tower range is the temperature difference between the entering and leaving cooling tower water temperatures. The range is one of the main targeted variables to optimize and does not require a calculation to solve, but it is an input to solve for other parametric values. As described in equation(4.1, the range has an inversely proportional relationship with the amount of heat rejected from the condenser water loop. As the range goes up, the condenser water flow rate must decrease, and as the range goes down, the mass flow rate must increase in order to reject the same amount of heat. It is important to understand that the condenser water plant “design range” and “operating range” are not the same. When the extra redundant pump is added, it creates a different operating range for a given cooling tower heat load. The condenser water plant experienced the operating range during a majority of the time. As a result, the operating range is the value that will be discussed in this paper. The operating ranges simulated in each location were 3°, 4°, 5°, and 6° C.

$$Q_{rejected} = \dot{m}_{cw} \times c_{p,water} \times Range \tag{4.1}$$

$Q_{rejected}$ Total amount of heat rejected
$Range$ Design condenser temperature range
$c_{p,water}$ Specific heat of water
$\dot{m}_{cw}$ Mass flow rate of condenser water

4.6.1.2 Cooling Tower Approach

The cooling tower approach measures how close the water leaving the cooling tower gets to the ambient wet-bulb temperature. In other words, it is the temperature difference between the water leaving the cooling tower and the outside wet-bulb temperature. The design value used for the design of the cooling towers was the 99.6% design evaporation condition. For each location, a cooling tower approach of 0.5°, 1°, 2°, and 3° C were simulated. In order to put these cooling tower approaches into EnergyPlus' Merkel Cooling Tower Model, each value was converted into an overall heat transfer coefficient. A new heat transfer coefficient was calculated in EES for each run at each location. The following steps describe the methods and formulas used to calculate the coefficient.

The first step is to apply conservation of mass and energy on the cooling tower. Equation (4.2), conservation of mass, expresses that the mass of the water entering the cooling tower equates to the amount of water collected in the basin of the cooling tower plus the water evaporated into the air. The unknowns in equation (4.2) were the mass flow rate of the water leaving the cooling tower and the humidity ratio of the air leaving the cooling tower. Equation (4.3) provides conservation of energy on the air and water going through the cooling tower to solve for the enthalpy of the leaving air.

$$\dot{m}_{water,out} + \dot{m}_{air,out} \times (\omega_{air,out} - \omega_{air,in}) = \dot{m}_{water,in} \tag{4.2}$$

$$\dot{m}_{water} \times c_{p,water} \times (T_{water,in} - T_{water,out}) = \dot{m}_{air} \times (h_{air,out} - h_{air,in}) \tag{4.3}$$

$\dot{m}_{water,in}$ Mass flow rate of water entering cooling tower
$\dot{m}_{water,out}$ Mass flow rate of water leaving cooling tower
$\dot{m}_{air,out}$ Mass flow rate of air entering cooling tower
$\omega_{air,in}$ Humidity ratio of air entering cooling tower
$\omega_{air,out}$ Humidity ratio of air leaving cooling tower
$\dot{m}_{water}$ Average mass flow rate of air entering and leaving cooling tower
$\dot{m}_{air}$ Average mass flow rate of air entering and leaving cooling tower
$T_{water,in}$ Temperature of water entering cooling tower
$T_{water,out}$ Temperature of water leaving cooling tower

$h_{air,in}$ Enthalpy of water entering cooling tower
$h_{air,out}$ Enthalpy of water leaving cooling tower
$c_{p,water}$ Specific heat of water

Equations (4.4) through (4.8) are typical counterflow heat exchanger equations. By combining the five heat exchanger equations, (4.4) through (4.8), with equations (4.2) and (4.3), and inputting all seven equations into EES, the overall heat transfer coefficient area product was calculated. However, before the final UA was calculated, the latent effect of air was considered.

$$\varepsilon = \frac{(T_{water,in} - T_{water,out})}{(T_{water,in} - T_{air,wb,in})} \tag{4.4}$$

$$\varepsilon = \frac{1 - exp\left\{-NTU\left[1 - \frac{\dot{C}_w}{\dot{C}_a}\right]\right\}}{1 - \frac{\dot{C}_w}{\dot{C}_a} \times exp\left\{-NTU\left[1 - \frac{\dot{C}_w}{\dot{C}_a}\right]\right\}} \tag{4.5}$$

$$\dot{C}_w = \dot{m}_{water} \times c_{p,water} \tag{4.6}$$

$$\dot{C}_a = \dot{m}_{air} \times c_{p,air} \tag{4.7}$$

$$NTU = \frac{UA_e}{\dot{C}_w} \tag{4.8}$$

ε Heat exchanger effectiveness
NTU Number of transfer units
$c_{p,air}$ Specific heat of air
UA_e Overall heat transfer coefficient-area product

To account for the heat rejection, in sensible and latent forms, a latent specific heat of air was estimated using equation (4.9). The final UA value was calculated using equation (4.10). These overall heat transfer coefficient values were entered into EnergyPlus.

$$\bar{c}_{pe,air} = \frac{(h_{air,out} - h_{air,out})}{(T_{air,wb,out} - T_{air,wb,in})} \tag{4.9}$$

$$UA = UA_e \times \frac{c_{p,air}}{\bar{c}_{pe,air}} \tag{4.10}$$

$\bar{c}_{pe,air}$ Mean specific heat of air
$T_{air,wb,in}$ Wet-bulb temperature of air entering cooling tower
$T_{air,wb,out}$ Wet-bulb temperature of air leaving cooling tower

UA Actual heat transfer coefficient

The cooling tower approach also determines the design cooling tower exit temperature. This was calculated by taking the design wet-bulb temperature and adding the cooling tower approach. The cooling tower design exit temperature was required as a cooling tower input for EnergyPlus.

4.6.1.3 Cooling Tower Fan Power and Air Flow Rate

The cooling tower air flow rate is a function of the fan power and fan efficiency. The first step was to determine the allowed motor power, per ASHRAE standard 90.1. The amount of fan power allowed by ASHRAE's Standard 90.1 (2019) is 40.2 GPM/HP (0.000003401 m^3/s/W). The fan power was calculated by using the 90.1 power standard with the flow rate of condenser water. For the axial cooling tower fan, the average pressure drop and fan efficiency were assumed to be 190 Pascals and 65 percent respectively. These values allowed for the air flow rate to be calculated using equation (4.12).

$$Power_{fan} = \dot{V}_{cw}/0.000003401 \tag{4.11}$$

$$\dot{V}_{air} = Power_{fan} \times \eta_{fan} \times \rho_{air}/190 \tag{4.12}$$

$Power_{fan}$ Fan power
$\dot{V}_{cw}$ Condenser water volumetric flow rate
$\dot{V}_{air}$ Cooling tower air volumetric flow rate
η_{fan} Fan efficiency
ρ_{air} Density of air

4.6.2 Heat Exchanger Approach

The heat exchanger approach is the difference between the chilled water temperature leaving the heat exchanger, and the temperature of the condenser water entering the heat exchanger. A lower approach will provide more free cooling hours. A small number of heat exchanger approaches were studied to find the optimum approach per location. The approaches studied were 0.5°, 1°, and 1.5° C. These approaches determined how cool the condenser water needed to get before the heat exchanger provided free cooling. Although the changes in the approach were small, there was a large difference in the required heat transfer surface and, therefore, the number of plates and associated cost to achieve these small changes in the approach. Since EnergyPlus requires the overall heat transfer coefficient (UA) for a simulated counterflow heat exchanger, UA was calculated from the approach. The heat exchanger was designed for equal flows on both sides on the heat exchanger.

$$T_{cws} = T_{chws} - HX_{approach} \tag{4.13}$$

$$\varepsilon = \frac{(T_{chwr} - T_{chws})}{(T_{chwr} - T_{cws})} \tag{4.14}$$

$$\varepsilon = \frac{NTU}{1 + NTU} \tag{4.15}$$

$$NTU = \frac{UA}{\dot{m}_{chw}} \tag{4.16}$$

ε Heat exchanger effectiveness
NTU Number of transfer units
UA Overall heat transfer coefficient
T_{cws} Required condenser water supply temperature
T_{chws} Chilled water supply temperature
T_{chwr} Chilled water return temperature
$\dot{m}_{chw}$ Mass flow rate of chilled water
$HX_{approach}$ Heat exchanger approach

First, equation (4.13) was used to solve for the required condenser water temperature for the approach. Next, equations (4.14) through (4.16) were entered into EES, as three equations and three unknowns, to solve for the heat exchanger's overall heat transfer coefficient.

The heat exchanger approach also determines the free-cooling temperature of the condenser loop. With a chilled water loop set point of 16.66° C, a heat exchanger approach of

0.5°, 1°, and 1.5° C will provide 100 percent free cooling at a condenser water temperature of 16.06°, 15.56°, and 15.06° C respectively. However, the low condenser water setpoints were allowed to go slightly lower to account for slight density differences between the chilled water loop and the condenser water loop.

4.6.3 Chiller Size

The size of the chiller was changed for each run so that it is appropriately sized for the corresponding cooling tower size. The bigger the cooling tower, the smaller the required chiller because there will be a slight decrease in lift. For this paper's simulations, the chiller was sized to be at 95% of maximum capacity at the design conditions. More information on the chiller model equations can be found in section 4.7.3. To calculate the chiller's reference size the design wet-bulb, each water loop's setpoint, and the design load were entered into the chiller's capacity, energy, and part load equations. These equations were then solved in EES with a 95 percent design part load capacity, to find the reference size of the chiller (Q_{ref}).

$$CAPFT = func[T_{chws}, T_{cws}] \tag{4.17}$$

$$EIRFT = func[T_{chws}, T_{cws}] \tag{4.18}$$

$$EIRPLR = func(PLR) \tag{4.19}$$

$$EIRPLR = \frac{P_{chiller}}{P_{ref} \times CAPFT \times EIRFT} \tag{4.20}$$

$$P_{ref} = \frac{Q_{ref}}{COP_{ref}} \tag{4.21}$$

$$PLR = \frac{Q_{design}}{Q_{available}} \tag{4.22}$$

$CAPFT$ Cooling capacity factor
$EIRFT$ Energy input to cooling output factor
$EIRPLR$ Energy input to cooling output factor

PLR Part load ratio
P_{chi} Chiller power use
P_{ref} Reference chiller power use
Q_{ref} Reference chiller load
COP_{ref} Reference chiller coefficient of performance
Q_{design} Design load
$Q_{available}$ Available cooling capacity

4.6.4 Condenser Water Flow Rate

Once the chiller's reference size was computed, the condenser water flow rate was calculated. Equations (4.23) through (4.25) solve for the design condenser water flow rate per pump. The total flow in the condenser water loop, with all four pumps running, was determined by multiplying the design flow rate of one pump by four.

$$Q_{rejected} = P_{chiller} * \eta_{chilller} + Q_{design} \tag{4.23}$$

$$\dot{m}_{cw} = \frac{Q_{rejected}}{Range \times c_{p,water}} \tag{4.24}$$

$$\dot{V}_{cw} = \frac{\dot{m}_{cw}}{\rho_{water}} \tag{4.25}$$

$Q_{rejected}$ Total amount of heat rejected
$P_{chiller}$ Power use of chiller
$\eta_{chilller}$ Amount of chiller heat rejected into condenser
Q_{design} Design chilled water load
$Range$ Design condenser temperature range
$c_{p,water}$ Specific heat of water
ρ_{water} Density of Water
$\dot{m}_{cw}$ Mass flow rate of condenser water
$\dot{V}_{cw}$ Volumetric flow rate of condenser water

4.6.5 Pump Flow, Head, and Power

The amount of pressure drop in the chilled water loop and the condenser water loop was used to determine each pumps design power. Table 4-1 shows the assumed design pressure drop for each component in the chilled water loop.

Table 4-1: Chilled water loop head losses

Component	Head Loss, kPa (ft w.g.)
Chiller Evaporator	35.87 (12)
Cooling Distribution Unit	59.78 (20)
Piping and Fittings	82.2 (27.5)
Heat Exchanger	68.75 (23)
Total	246.59 (82.5)

The pump design power was calculated using the total design head loss, the design chilled water flow rate of 0.177 m^3/s (2800 GPM), and a pump efficiency of 90 percent. Using equation (4.26), the power for each pump was 65 HP or 48,470 W.

$$P_{chw,pump} = \frac{Q \times h}{3960 \times \eta_{pump}} \tag{4.26}$$

$P_{chw,pump}$ Pump power
η_{pump} Pump efficiency
Q Pump volumetric flow rate
h Pump head

The design head loss in the condenser water loop depended on the design range. As a result, a base set of pressure losses were created for each component, but each run was adjusted to account for the specific range. Table 4-2 shows the base condenser loop pressure drops at the industry standard condenser water flow rate of 0.054 ml/J (3 GPM/Ton). The condenser's head loss was adjusted for each new range using a quadratic relationship between pressure and flow rate. The cooling tower pressure drop was assumed to be mostly static head, so it was held constant for all ranges. The pipe's and fitting's total head losses were held constant for each range, but the pipe size was adjusted to keep a constant head loss per foot of pipe.

Table 4-2: Condenser water loop pressure drops

Component	Head Loss, kPa (ft w.g.)
Chiller Condenser	35.87 (13)
Cooling Tower	59.78 (14)
Piping and Fittings	82.2 (19)
Heat Exchanger	68.75 (23)

In the condenser water loop, there were three different modes of flows and pressure drops. These modes include full mechanical cooling, partial economizing/partial mechanical cooling, and full economizing. Each of these modes had a different flow rate and pressure drop for each range. To get the total required pump head, each mode was graphed using DView and the total design head was solved from the Dview outputs. This approach ensured the pump was designed for the highest power required during the annual simulations.

4.7 EnergyPlus Component Models

The main EnergyPlus components used in this study were the cooling tower, heat exchanger, and chiller. This section will summarize the computational models chosen along with any other applicable information on the controls used in the simulations.

4.7.1 Cooling Tower Model

The cooling tower model used in the simulations was based on Merkel's theory, which models cooling towers as counter-flow heat exchangers between the air and water (DOE, 2019).

The EnergyPlus model, includes Scheier's adjustments, which account for the current wet-bulb, and current water and air flow rates (DOE, 2019).

For the simulations, all four cooling towers were run constantly with the load evenly divided among the towers. The plant had the potential to run at design conditions with only three cooling towers because of the "N+1" design redundancy provided. However, it is advantageous to always use all the cooling towers when available.

The cooling tower controls included variable air and water control. If the temperature of the condenser water was over the free-cooling setpoint, the fan and pumps were run at 100 percent. Once the condenser water temperature dropped below the free cooling setpoint, the fan speeds and pump speeds were reduced to maintain the free cooling setpoint and minimize energy use. The fan was allowed to turn off during low wet-bulb periods, however this was a rare occurrence. The minimum water flow rate through a cooling tower was fifty percent. According to several manufacturers, operating under a fifty percent flow rate can create freezing problems. No other freezing precautions were taken into account for the simulation because of the high condenser water temperatures used. Additionally, the load was assumed to be constant throughout the whole year without shutting down and cooling off.

4.7.2 Heat Exchanger Model

The plate and frame heat exchanger in the model was simulated by a single generic counterflow fluid-to-fluid heat exchanger. This heat exchanger transfers heat from the chilled water loop to the condenser water looped so it can be rejected by the cooling towers. The heat exchanger is placed upstream of the chillers, in the chilled water loop, in an "integrated" configuration.

The heat exchanger became active once there was at least a calculated 1° C temperature change in the chilled water loop as a result of activating the heat exchanger. If there was not a 1° C temperature, the heat exchanger was bypassed in both the chilled water and condenser water loops. The flow rate through the heat exchanger was controlled so that it was equal to the design flow rate on the chilled water loop and less than or equal to the design flow in the condenser water loop.

4.7.3 Chiller Model

The water-cooled chillers were modeled using the "Electric Chiller Model Based on Condenser Entering Temperature" model used in EnergyPlus (DOE, 2019). It utilizes three performance curves including the Cooling Capacity Function (CAPFT), Energy Input to Cooling Output Ratio Function (EIRFT), and the Energy Input to Cooling Output Ratio Function of Part Load Ratio (EIRPLR) to adjust the capacity for non-reference conditions (DOE, 2019).

The chiller was modeled after a Carrier 19FA with a reference coefficient of performance (COP) of 5.5 at 29.3° C condenser water supply temperature and a 6.67° C chilled water temperature. The performance curves for this chiller required the chilled water supply temp to be between 4.49°C and 8.89° C, which does not include the chilled water setpoint of 16.66° C for class W1. To accurately model this chiller, at the design supply temperature, the chiller's performance curves were translated. A translation is a movement of the graph either horizontally parallel to the x-axis and/or vertically parallel to the y-axis. The chiller performance curves were shifted to include the chilled water setpoint in the translated limits. To translate the chilled water model, the chilled water temperature $(T_{chws} - 8.3)$ was substituted for (T_{chws}) to shift the performance curves 8.3° C warmer.

$$CAPFT = func[T_{chws}, T_{cws}] \tag{4.27}$$

$$CAPFT_{shifted} = func[(T_{chws} - 8.3), (T_{cws})] \tag{4.28}$$

$$EIRFT = func[T_{chws}, T_{cws}] \tag{4.29}$$

$$EIRFT_{shifted} = func[(T_{chws} - 8.3), (T_{cws})] \tag{4.30}$$

$CAPFT$ Cooling capacity factor
$EIRFT$ Energy input to cooling output factor
$EIRPLR$ Energy input to cooling output factor
T_{chws} Chilled Water supply temperature
T_{cws} Condenser water supply temperature

In addition to adjusting the chiller curves, the reference COP was also changed to account for the reduced lift on the chiller. This COP calculation was done by comparing the Carnot Cycle COP on the original, reference conditions, to the translated condition, as shown in equation (4.31). The results are all summarized in Table 4-3.

$$\frac{COP_{new}}{COP_{ref}} = \frac{COP_{carnot,new}}{COP_{carnot,ref}} \tag{4.31}$$

$$COP_{carnot} = \frac{T_L}{T_H - T_L} \tag{4.32}$$

$COP_{carnot,new}$ Carnot efficiency with translated temperatures
$COP_{carnot,ref}$ Carnot efficiency with reference temperatures
COP_{new} Coefficient of performance of translated curves
COP_{ref} Reference coefficient of performance
T_L Temperature of chilled water
T_H Temperature of condenser water

Table 4-3: Translated chiller limits and COP

	Chill Min	Chill Max	Cond Min	Cond Max	COP
Initial (°C)	4.49	8.89	15.56	29.44	5.5
Translated (°C)	12.79	17.19	15.56	29.44	8.94

Chapter 5

Results and Analysis

5.1 Introduction

This chapter presents results of the parametric study. A total of forty-eight different configurations were simulated for each location and several outputs were recorded: annual energy use, and the time in full economizing, partial economizing, and full mechanical cooling modes. Since EnergyPlus has life-cycle energy cost (LCC) calculation capabilities, the fifteen-year utility cost present value was also recorded. The analysis is split into two categories: energy and LCC. The energy section will go over all energy savings by utilizing a waterside economizer for a liquid-cooled data center. Furthermore, the optimized simulations, at all the locations, will be compared with its corresponding wet-bulb profile to form general rules and best practices for data centers. In the LCC section, a cost analysis will be completed on each of the simulations to determine if further increasing economizer components could also have monetary benefits in addition to energy savings.

5.2 Energy Use Results

5.2.1 Chicago

The waterside economizer performed well in Chicago, Illinois, which was likely due to the fact that Chicago has a relatively dry and cold climate. Figure 5-1 shows the energy results from running the forty-eight simulations in Chicago. The left vertical axis represents the cooling tower approach, the right vertical axis is grouped by the cooling tower range, and the color of each point represents the heat exchanger approach. The horizontal axis shows annual energy use in gigajoules, with energy use increasing from left to right. As expected, larger heat exchangers (lower heat exchanger approach), or larger cooling towers (lower cooling tower approach), will decrease the overall energy use. Furthermore, the results show that increasing the size of the cooling tower is more beneficial than increasing the size of the heat exchanger. For example, point one has a cooling tower approach of 1° C and a heat exchanger approach of 1° C. Point two represents increasing the heat exchanger size to an approach of 0.5° C and point three represents increasing the cooling tower size to a cooling tower approach by 0.5° C. It can be observed, when comparing the distance between point one and two, and point one and three, that the energy savings are larger from point one to three than they are from point one to two. Therefore, increasing the size of the cooling tower over the heat exchanger will save more energy annually because of the increased performance of the chiller. The optimum range for Chicago was 5° C.

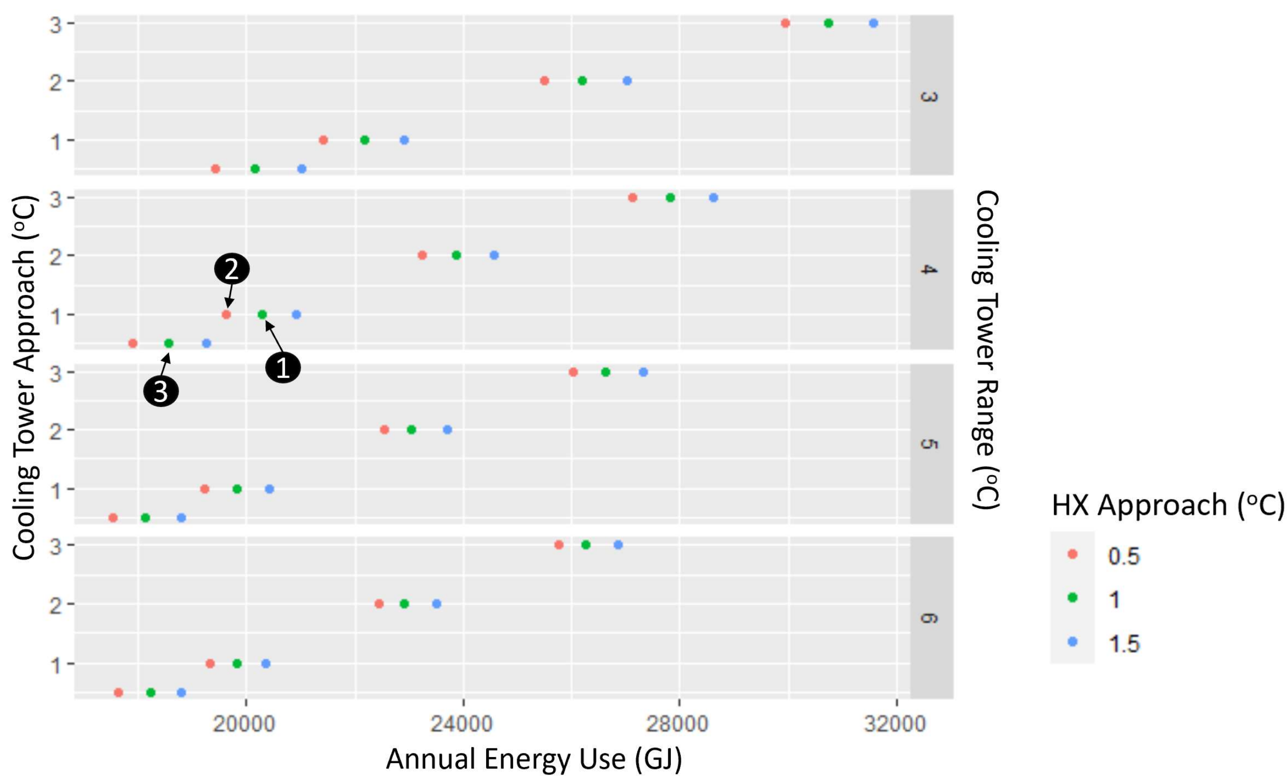


Figure 5-1: Chicago energy use simulation results

The full economizing hours, partial economizing hours, and full mechanical cooling hours of the year are displayed below in Figure 5-2. The horizontal axis is a table that shows the design parameters of each simulation. It can be noticed that the lower the approach, of either the cooling tower or the heat exchanger, the higher the number of partial and full economizing hours. This figure also shows that the number of full economizing hours decreases as the range increases. Looking at the peaks of the of the full economizing bars in blue, the peaks slightly decrease as the range increases. This can be seen by comparing the two dashed lines on the plot. The top is perfectly horizontal, and the bottom line follows a cooling tower approach of 0.5° C. This decrease in hours, however, does not make up for the extra energy used by pumping according to Figure 5-1.

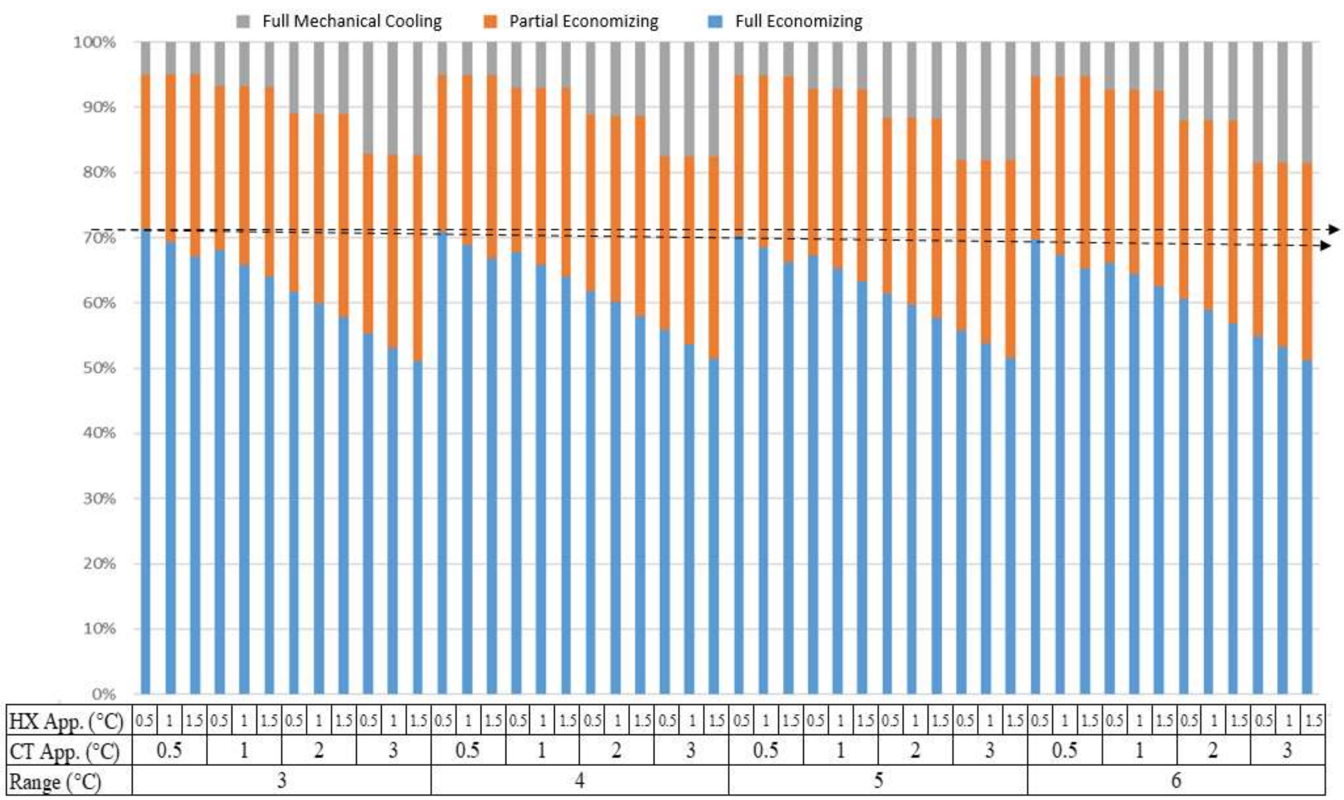


Figure 5-2: Chicago time distribution of economizer modes as a function of approach and range

5.2.2 Dallas

Dallas, Texas is the warmest, and the most humid, location that was tested. The results of the parametric study for Dallas are shown in Figure 5-3. Like Chicago, and as expected, the lower design approaches yielded more energy savings, even in the warm and humid climate of Dallas. Looking at the optimal results of each cooling tower range, one would notice the results did not optimize in the selected ranges. To find the optimum range, more simulations were completed. Although it is not shown in Figure 5-3, the range became optimized at 7° C. This high range is because Dallas had the least number of economizing hours and the extra pump and fan energy used for lower ranges was not made up for with economizing savings.

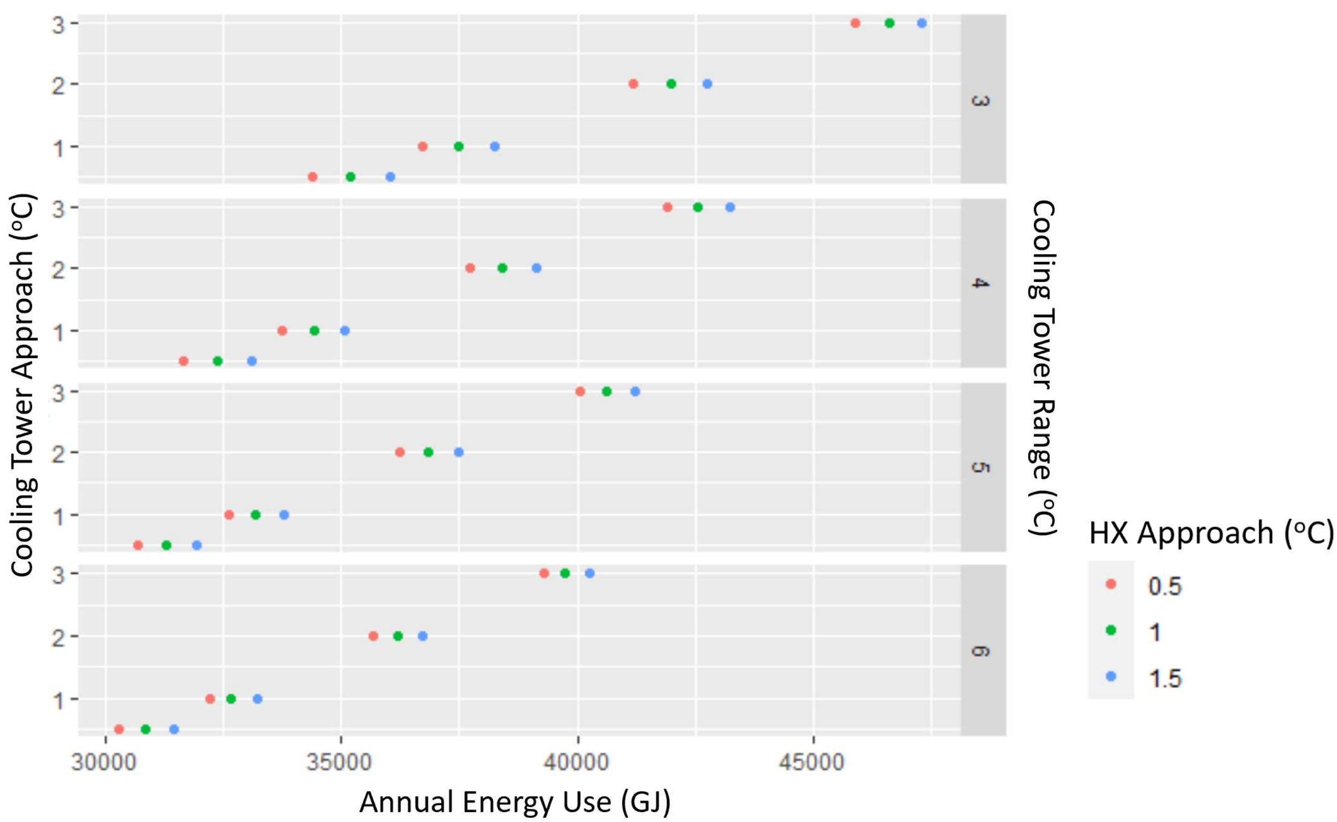
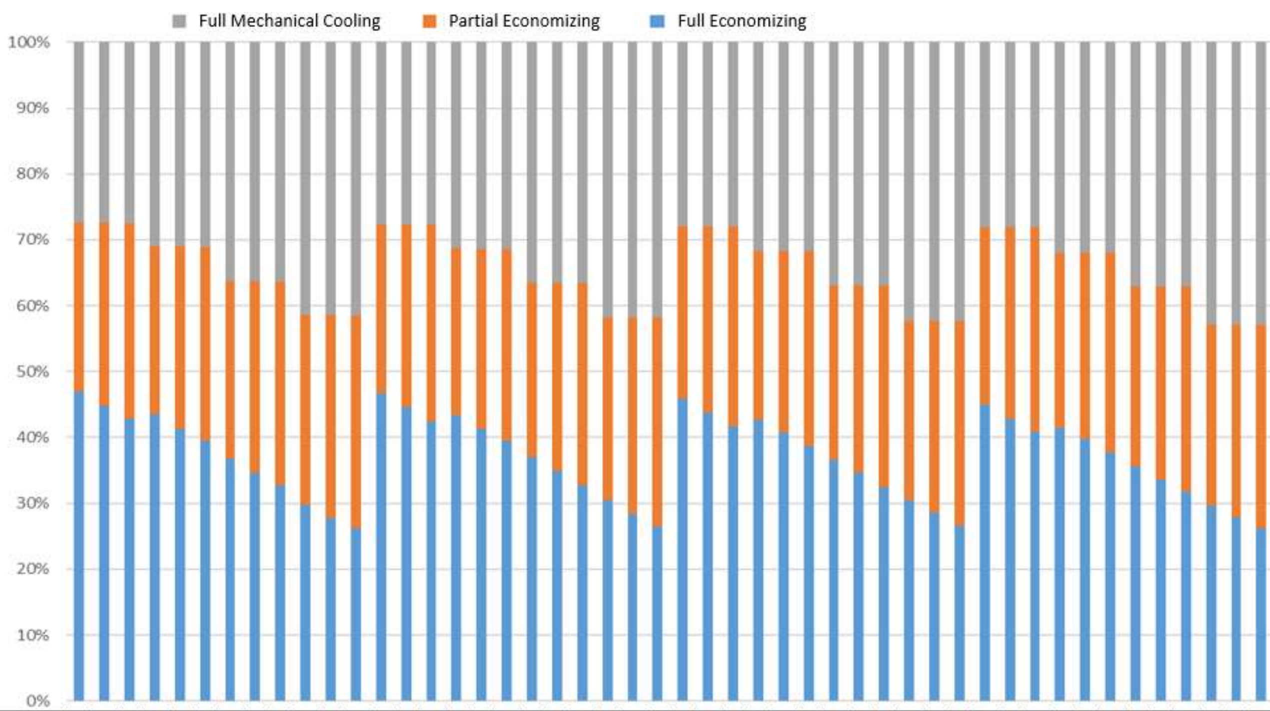


Figure 5-3: Dallas energy use simulation results

The annual status of the economizer in Dallas is displayed for each simulation run in Figure 5-4. At first glance, the amount of time in full economizing, or partial economizing, is less than Chicago's economizer run percentages. However, this was expected with a more humid climate. Nevertheless, the simulations that used the least total energy still have around forty-five percent of annual hours in free-cooling mode, so the expected energy savings are still significant.



<table>
<tr><td>HX App. (°C)</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td><td>0.5</td><td>1</td><td>1.5</td></tr>
<tr><td>CT App. (°C)</td><td colspan="3">0.5</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td><td colspan="3">0.5</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td><td colspan="3">0.5</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td><td colspan="3">0.5</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td></tr>
<tr><td>Range (°C)</td><td colspan="12">3</td><td colspan="12">4</td><td colspan="12">5</td><td colspan="12">6</td></tr>
</table>

Figure 5-4: Dallas time distribution of economizer modes as a function of approach and range

5.2.3 Salt Lake City

Next, simulations were run in the driest of the five selected locations, in Salt Lake City, Utah. Salt Lake City was expected to perform advantageously with a waterside economizer because of its dry climate. The energy results of all the Salt Lake City simulations are summarized in Figure 5-5. The spread of the results look like Chicago and Dallas for the most part, but the annual energy use is far lower with some results under 10,000 GJ per year. The range that used the least amount of energy in these simulations was 4° C. This range of 4° C is significant because if proves that it can be beneficial, for energy use, to use lower than typical ranges for increased waterside economizer performance. The reason why the range performed better at a lower range in discussed in section 5.2.7.

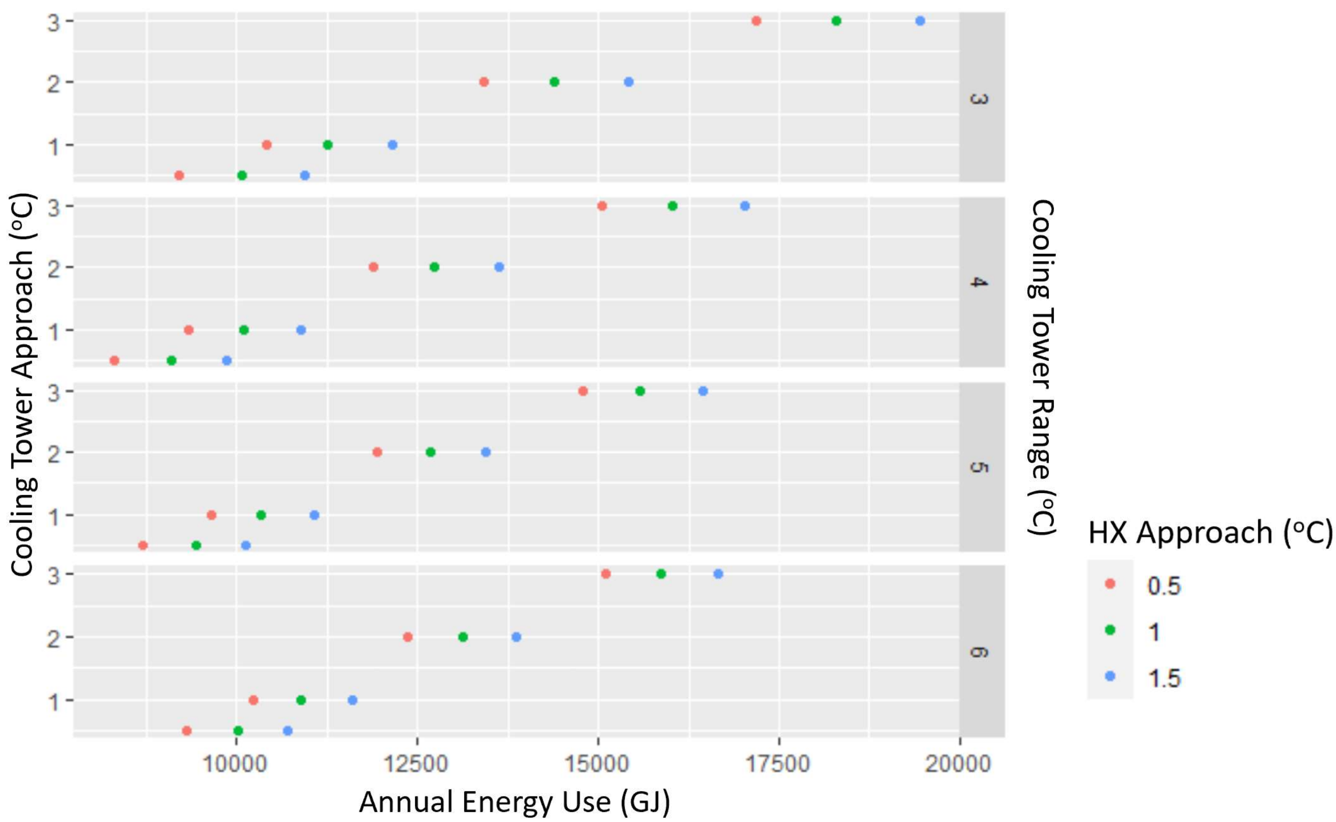


Figure 5-5: Salt Lake City energy use simulation results

The low annual energy use of the data center in Salt Lake City was due to the high number of economizing hours shown in Figure 5-6. In fact, full mechanical cooling was never required for any of the simulation runs. In this research, the economizing system's heat exchanger was considered non-mission essential and the chillers were considered essential. However, if the waterside economizer components were also considered mission critical, the size of the chiller could be decreased. This alternative design would change the chiller's design load to a partial economizing mode which would largely decrease the size of the chiller.

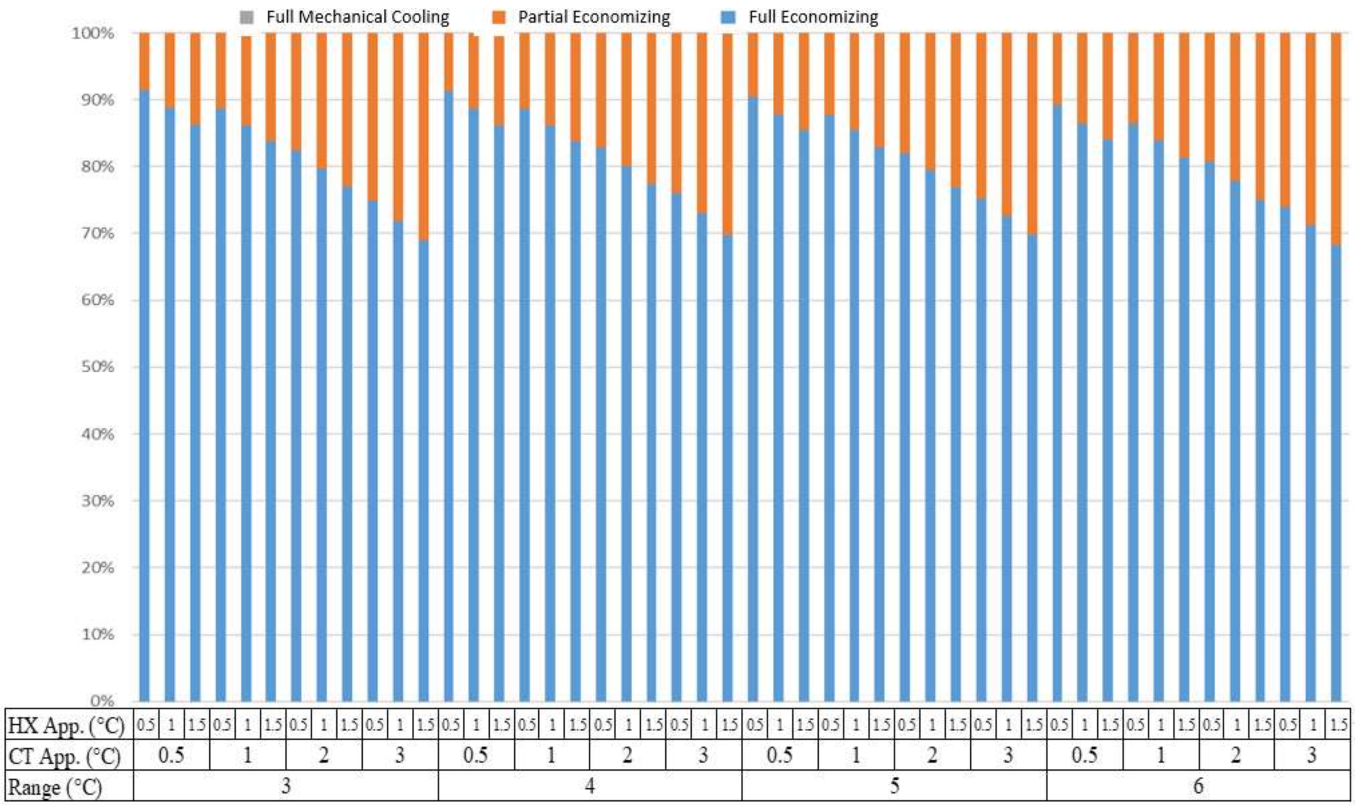


Figure 5-6: Salt Lake City time distribution of economizer modes as a function of approach and range

5.2.4 San Jose

San Jose, California, is a marine climate where the wet-bulb temperature has a smaller range of extremes when compared to the other climates in this study. The results of the parametric study of San Jose are displayed in Figure 5-7. Like Salt Lake City, San Jose had low annual energy use compared to Dallas and Chicago. The large energy saving of San Jose savings come from the fact that San Jose's wet-bulb rarely gets high enough to require full mechanical cooling. Also similar to Salt Lake City, the lowest energy use was achieved with a range of 4° C.

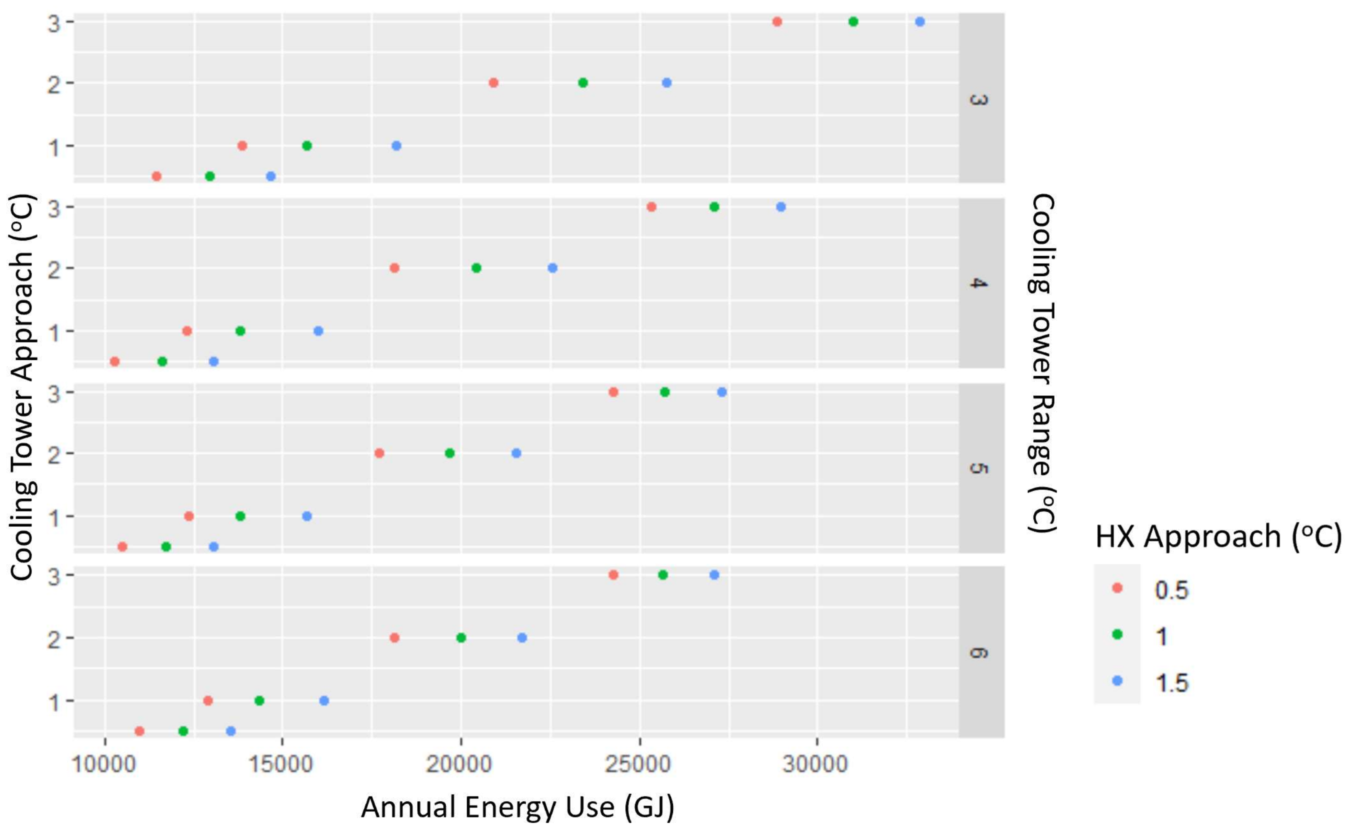


Figure 5-7: San Jose energy use simulation results

The annual economizer status is shown in Figure 5-8 below. Almost the entire year is in full or partial economizing mode. Although it is too small to see in this chart, all the simulations with at a 1° C cooling tower approach or less, did not require any time in full mechanical cooling. Therefore, like Salt Lake City, the chillers have the potential to be downsized if the waterside economizer is designed as a mission critical component.

In the chart below, there is a large difference between amount of free cooling between the runs of San Jose. For example, in the 4° C range block on the left side, as the approach of the components decrease or as the economizer components size increase, the time in full economizing mode goes up from thirty-five percent to eighty-five percent. This large increase is due to how flat San Jose's wet-bulb duration curve is in Figure 4-1. As visualized in the duration curve, lower approach components for San Jose can add substantially more economizer hours versus a climate with a more sloped duration curve like Chicago.

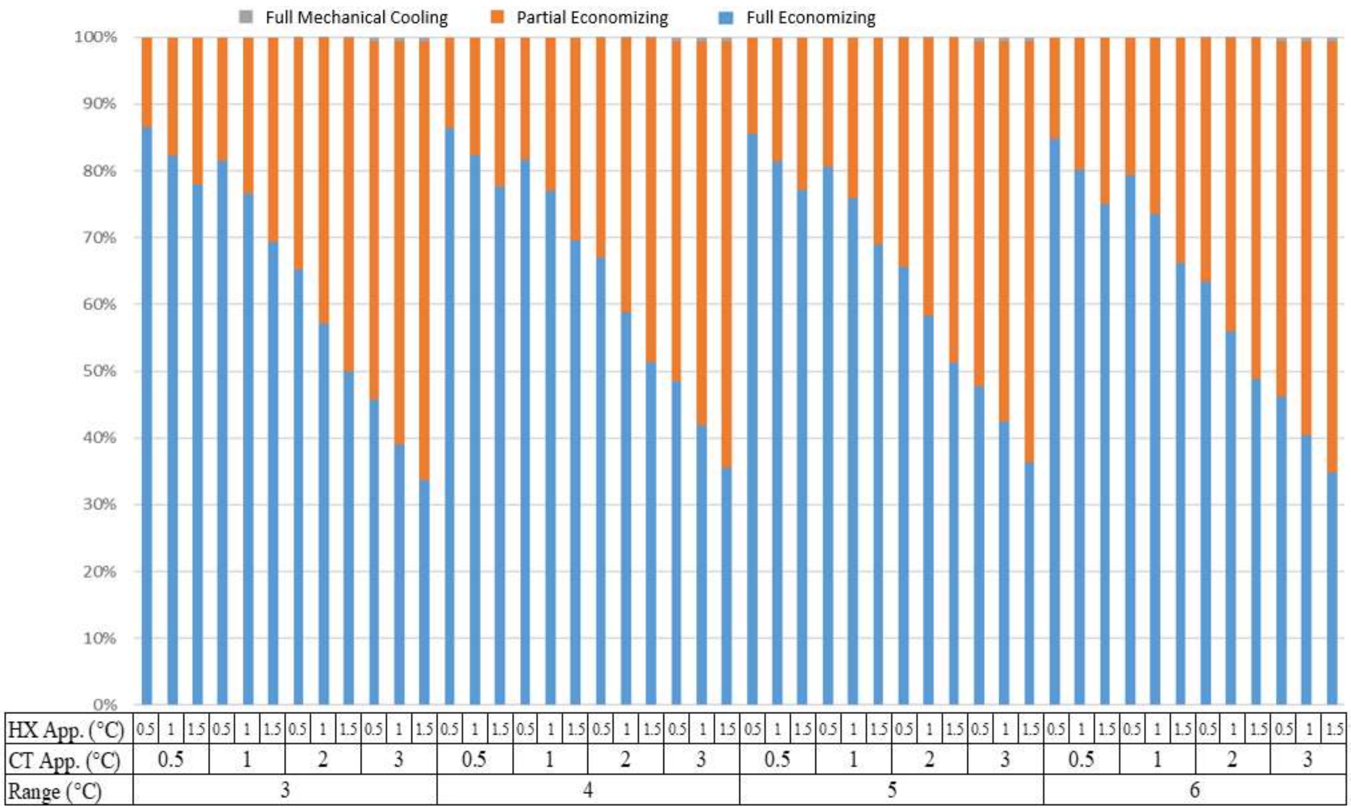


Figure 5-8: San Jose time distribution of economizer modes as a function of approach and range

5.2.5 Washington DC

Washington DC has a very similar climate to Chicago, but the wet-bulb temperature tends to be few degrees warmer. The results of the Washington DC simulations, shown in Figure 5-9, also look very similar to Chicago's simulations, just slid slightly to the right. The optimum range for Washington DC was 6° C. No additional unique results were generated from this set of simulations.

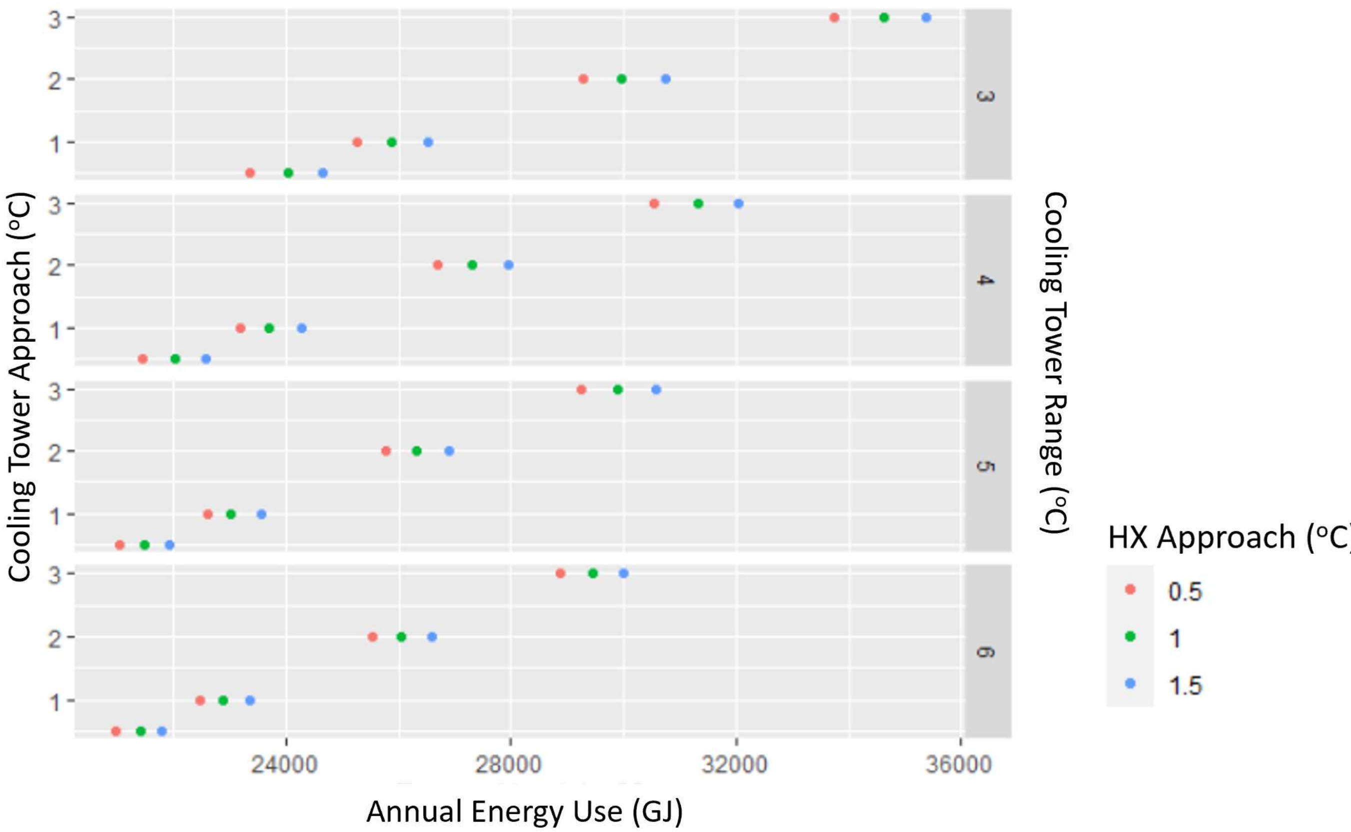


Figure 5-9: Washington DC energy use simulation results

The annual economizer status for the simulations in Washington DC are in Figure 5-10. Once again, the results look like Chicago's with just slightly less economizing time.

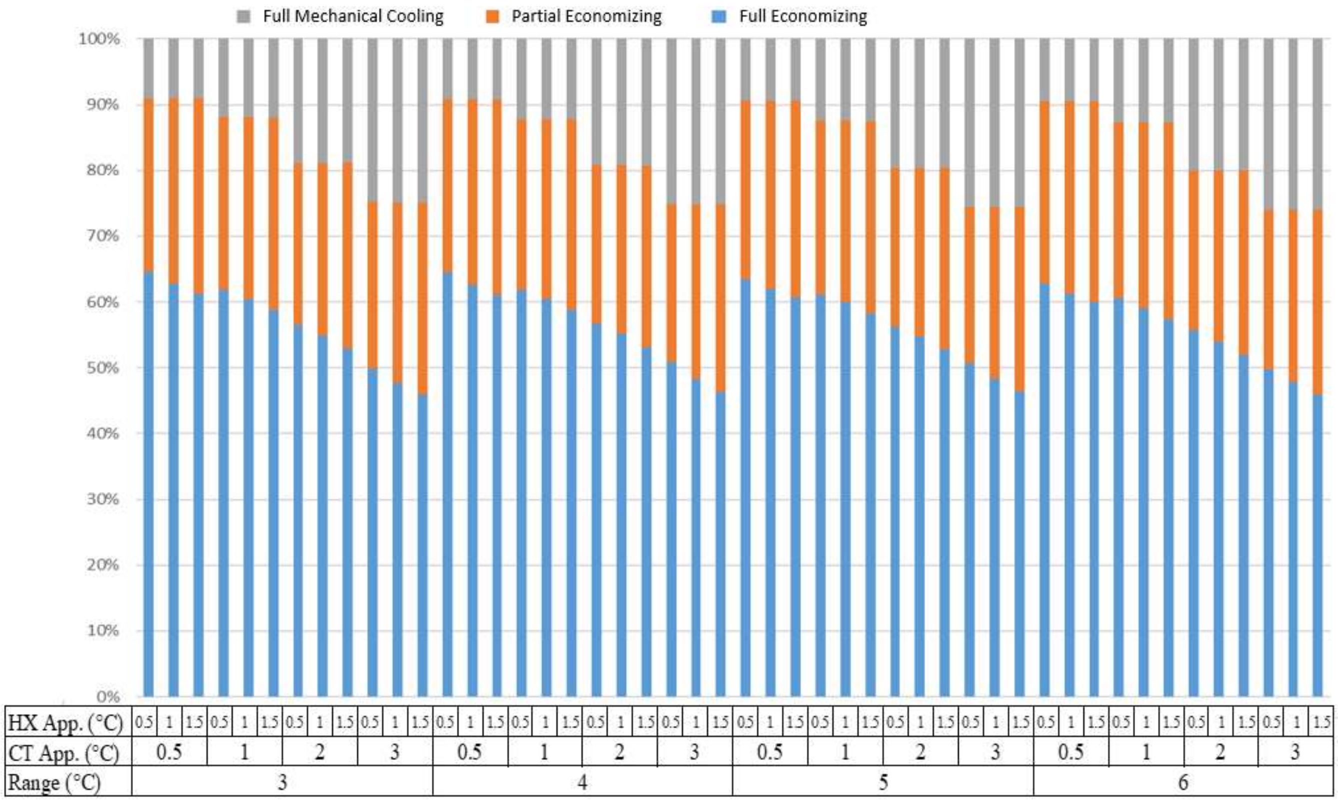


Figure 5-10: Washington DC time distribution of economizer modes as a function of approach and range

5.2.6 Summary of Waterside Economizer Energy Savings By Location

In addition to the parametric study, a baseline simulation was done at each location to determine the energy use without a waterside economizer (WSE) for the purpose of calculating WSE savings. The baseline model includes a chiller plant with a cooling tower approach of 3° C and an operating range of 5° C. Although a data center without any type of energy saving technology would not be the ideal design, the energy use numbers do show the potential energy savings when compared to other methods in literature. The baseline energy use, presented in Figure 5-11, in each location is so high because the chillers are operating in a minimum lift situation for a large part of the year. The “Typical WSE” column below is the baseline model, plus a 3° C approach cooling tower and a 1.5° C approach heat exchanger. This “Typical WSE” configuration is based on the typical component sizes recommended in current literature. These savings with just the waterside economizer are substantial but it was the intent of this paper is to further expand on the sizing of components for additional energy savings. The chart and table show that there are unlocked energy savings with optimizing the cooling tower approach, range, and heat exchanger approach for all the locations. Note, that the optimum values refer to optimum energy use and not cost, which will be discussed in section 5.3.2.

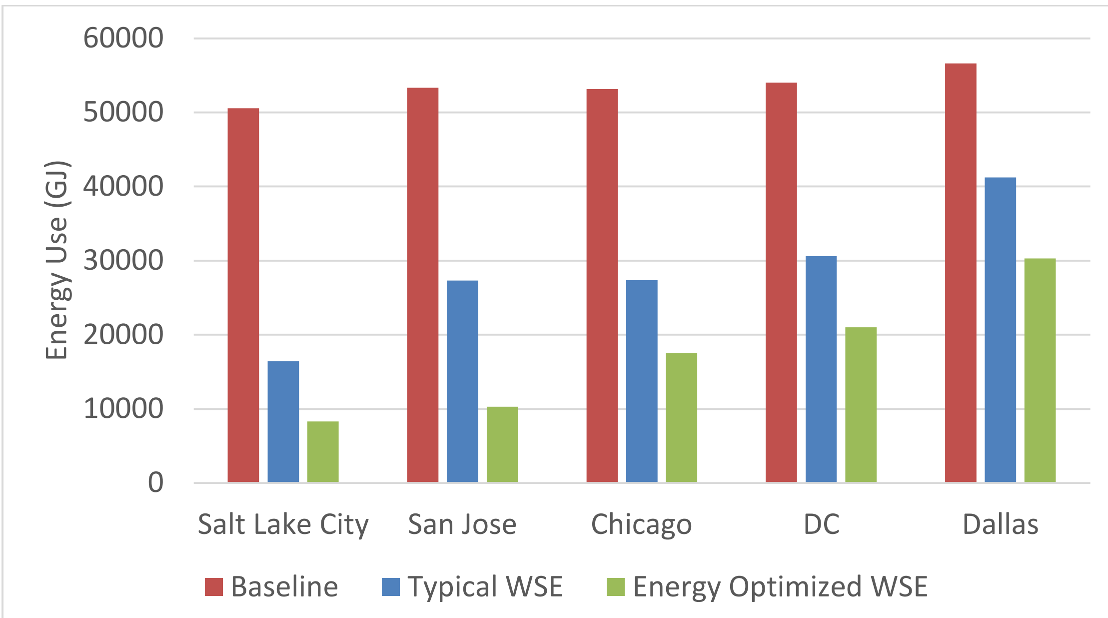


Figure 5-11: Energy savings of optimized waterside economizers

Table 5-1: Waterside economizer percent annual energy savings versus baseline system

Percent Annual Energy Savings vs Baseline System		
Location	Typical WSE	Energy Optimized WSE
Salt Lake City	67.49%	83.56%
San Jose	48.75%	80.70%
Chicago	48.57%	67.00%
DC	43.38%	61.13%
Dallas	27.15%	46.48%

5.2.7 Effect of Climate on Energy Use

To gain knowledge of waterside economizer performance, a location's wet-bulb characteristics were compared with waterside economizer performance for each location. The wet-bulb characteristic chosen for this study was a location's Wet-Bulb Degree-Days (WBDD). The concept of WBDD is very similar to the concept of Cooling Degree-Days (CDD). The WBDD in this report was calculated relative to a base of to 16.7° C (62° F). For example, if a day had a mean wet-bulb temperature of 20.7° C, it would be a total of 4 WBDD. The total wet-bulb degree days for the five locations are displayed in Table 5-2. The WBDD should be a good predictor as to how much compressor energy is required for each location. Different data center classes, with different chilled water setpoints, would require a different WBDD base temperature which was a good predictor of compressor energy use.

Table 5-2: Wet-bulb degree-days per location

Location	WBDD_16.7
Salt Lake City	8
San Jose	27
Chicago	269
Washington DC	407
Dallas	856

The total WBDD for each location was plotted against the location's minimum energy use for the simulation. This graph, shown in Figure 5-12, reveals a linear trend in the energy use. This idea could be extended to estimate the energy use, in other locations, with comparable ITE load profiles.

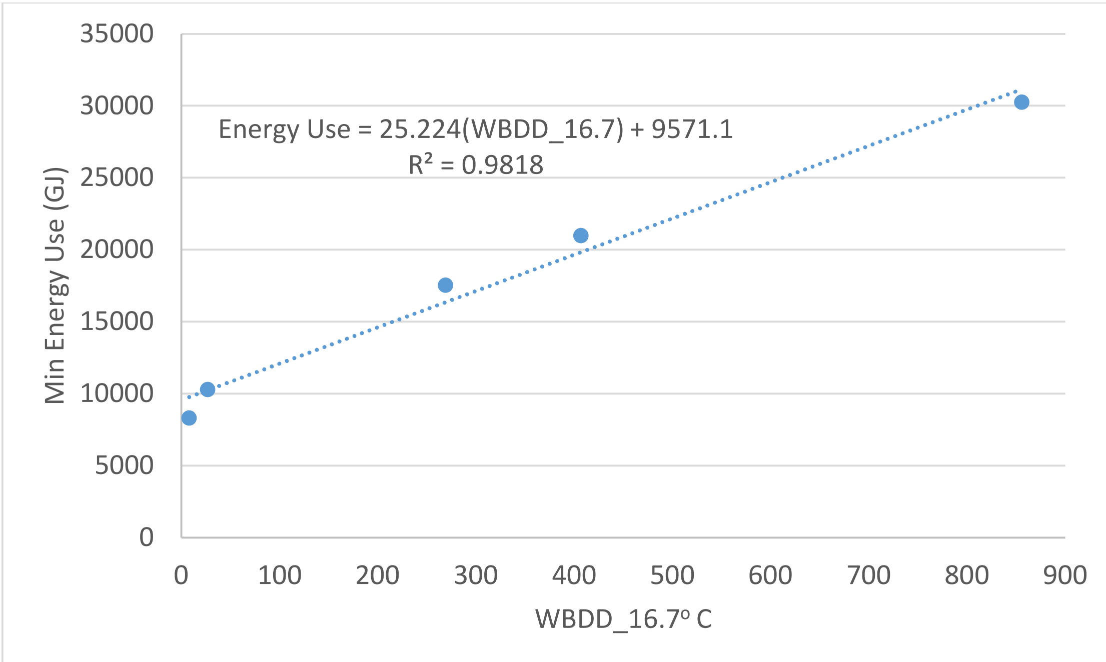


Figure 5-12: Minimum energy use vs WBDD

The WBDD concept can be further extended to economizer function. The total time in full economizing mode, and the total time in full and partial economizing mode, for each location, are displayed in Figure 5-13. Again, there is a strong linear correlation from the number of economizing hours to the WBDD. If there was a data center with a constant ITE load, and class W1 equipment, these linear relationships would be a quick way to figure out the predicted number of economizing hours. Furthermore, this graph also shows something that was not derived in the energy use plots. As a waterside economizer moves to more humid locations, the amount of time spent in partial cooling increases when compared to less humid locations. This can be seen on the chart as the lines open-up, like in a cone shape, when looking left to right. The more partial economizing required, at more humid locations, increased the total output of the pumps, because the condenser water flow rate had to be divided and supplied to both the chiller's condensers and the heat exchanger.

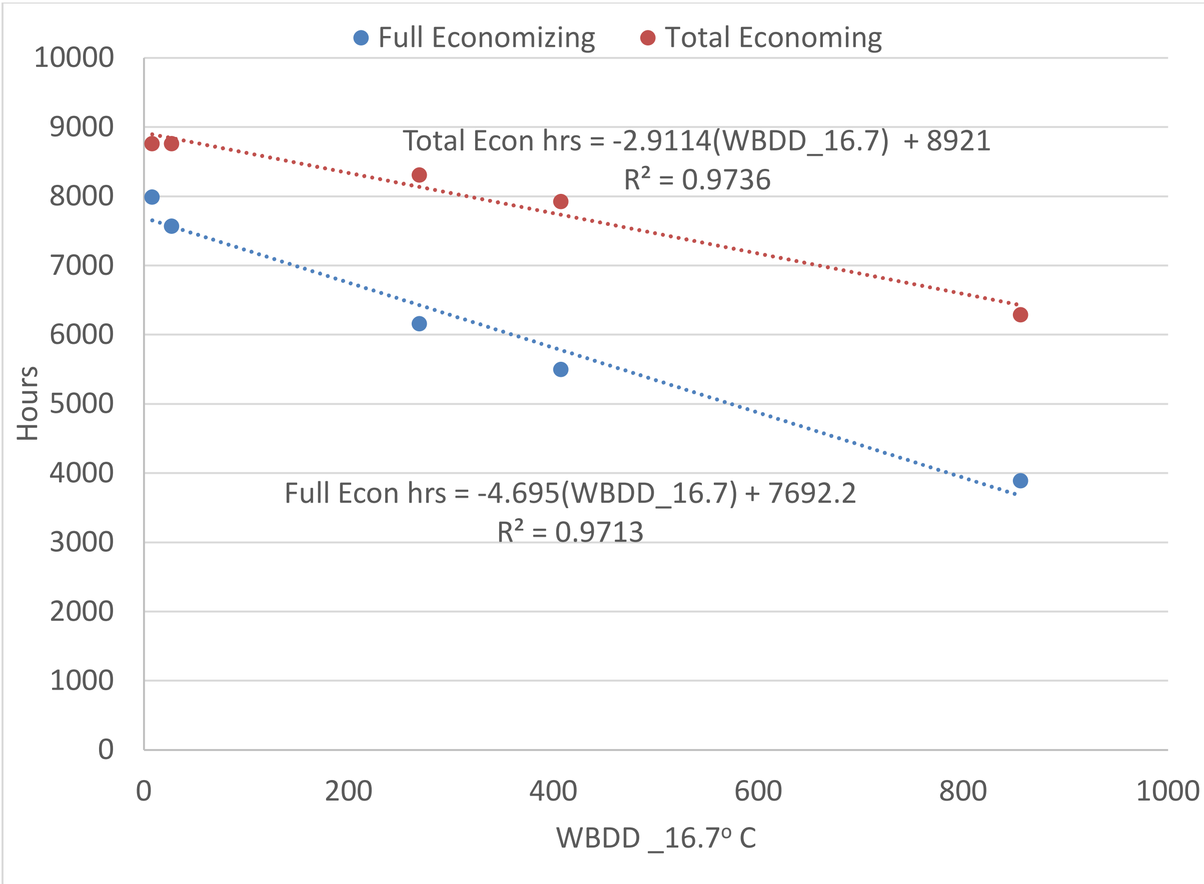


Figure 5-13: Economizer function vs WBDD

The last connection made with WBDD was against the optimized range. It was hypothesized that a decreased range may be beneficial for waterside economizers. It turns out to be slightly more complicated. As Figure 5-14 shows, a decreased range is beneficial for locations that spend a significant portion of the year in a waterside economizing mode. It was beneficial for the locations like San Jose, and Salt Lake City, which had a large amount of free-cooling hours. However, the other locations did not benefit from using a "low" condenser range. The lower ranges had the benefit of providing more flow to the heat exchanger during partial economizing. The increased flow in the heat exchanger decreased the load on the chiller. This concept is displayed in Table 5-3, which shows that as the range went down, so did the chiller load during partial economizing. The data, for Table 5-3, was gathered from Chicago, with a cooling tower approach of 0.5° C and a heat exchanger approach of 0.5° C. Additionally, the lower ranges added slightly more free-cooling hours, as shown in Figure 5-2. On the other hand, the higher ranges used less pump and fan energy during full mechanical cooling operation. Therefore, the higher ranges performed better when locations, or configurations, required more time in full mechanical cooling mode.

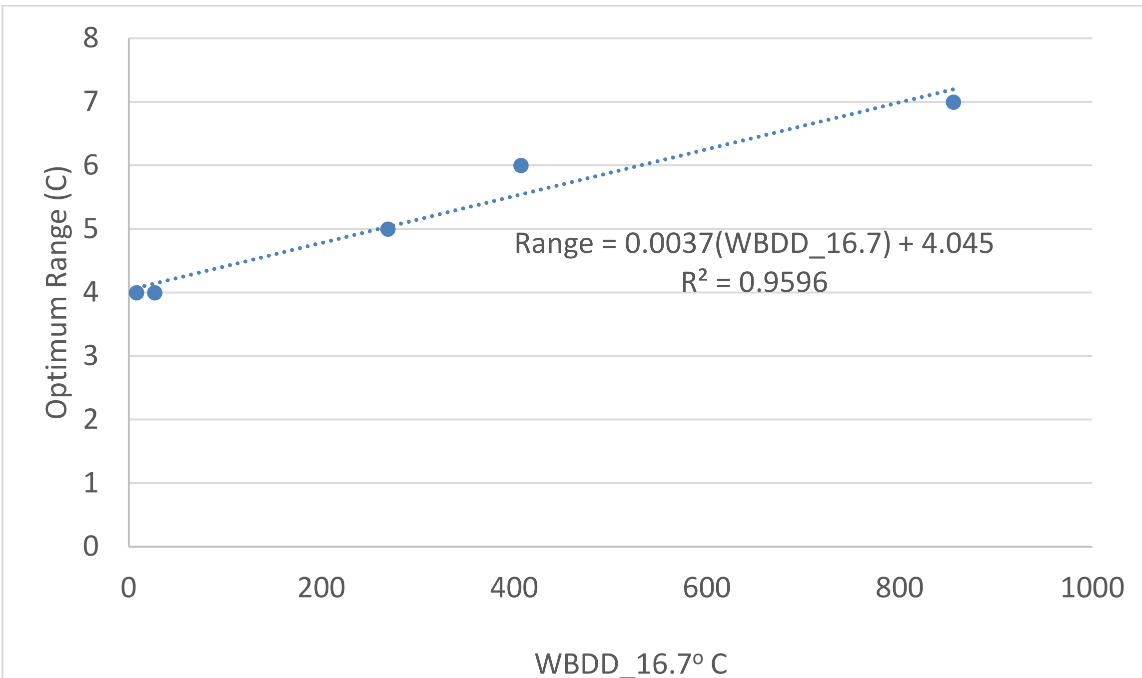


Figure 5-14: Optimum range vs WBDD

Table 5-3: Chiller's load during partial economizing as a function of range

Partial Economizing Average Load	
Range (° C)	Chiller Load (Percent of Design Load)
3	55.6
4	59.9
5	62.4
6	65.1

5.3 Life Cycle Cost

In the last section it was proved that further decreasing the cooling tower and heat exchanger approach, plus using an optimized range, can further increase energy savings. However, the question on whether this technique should be applied in an actual data center depends on the increased cost of the waterside economizer components. To answer this question, a life cycle cost (LCC) analysis was completed on all forty-eight simulations per location along with the baseline configuration. Note that this LCC is comparative and not all-inclusive. For example, the chiller capitol cost and maintenance costs would be approximately the same for all the designs and thus it was not included in the LCC.

5.3.1 LCC Assumptions and Data Collection

The capitol costs included in the LCC are the heat exchanger, cooling towers, condenser water pumps, and condenser water piping and fittings. The utilities included are electricity and water. The electricity price was assumed to be a constant rate for this LCC. The optimum utility structure of a data center could be a research project within itself and thus a flat rate was chosen to isolate the savings of the WSE. Table 5-4 below summarizes the costs used for the LCC calculation.

The LCC analysis was completed with a duration of fifteen years. This is shorter than the average building life cycle however it was the recommended timeframe (Donovan, 2013). The shorter life cycle of a data center is largely since the servers become outdated and need to be replaced every two to five years which may change the building’s requirements. For the fifteen-year LCC, each location’s calculation used the corresponding NIST escalation factor and discount rate, to adjust all costs back to a present value (Lavappa & Kneifel, 2019). The cost for all the configurations at each location are summarized in Appendix B.

Table 5-4: LCC data

<table>
<tr><th>Line Item</th><th colspan="2">Cost Data Collection Method</th></tr>
<tr><td>Cooling Tower</td><td colspan="2">The cooling tower costs were collected with a free pricing tool from the Cooling Tower Depot (Design and Price a New Tower, 2020). The prices ranged from about $400K for a set of towers with an approach of 3° C to about $1.5M for an approach of 0.5° C.</td></tr>
<tr><td>Heat Exchanger</td><td colspan="2">The heat exchanger prices are based off a paper that found a trend in plate and frame heat exchanger cost vs heat exchanger area (Hewitt & Pugh, 2007). The data from the article was adjusted for inflation. The price of the heat exchangers used is $508k, $254k, $164k, for an approach of 0.5°, 1°, and 1.5° C respectively.</td></tr>
<tr><td>Piping and fittings</td><td colspan="2">The pipe and fitting cost data was taken from RSMeans (RSMeans Commercial New Construction, 2020). It was assumed that the condenser water system was 750 feet and an extra twenty five percent was added for increased fitting cost.</td></tr>
<tr><td>Pumps</td><td colspan="2">The pump data was also taken from RSMeans (RSMeans Commercial New Construction, 2020). The price increased about $5K per pump to decrease the range by 1° C.</td></tr>
<tr><td rowspan="6">Electric Rates</td><td colspan="2">The electric rate was taken from the average industrial electric rate per city (Electricity Rates and Usage, 2020).</td></tr>
<tr><td>Chicago</td><td>5.89 ¢/kWh</td></tr>
<tr><td>San Jose</td><td>8.98 ¢/kWh</td></tr>
<tr><td>Salt Lake City</td><td>5.48 ¢/kWh</td></tr>
<tr><td>Washington DC</td><td>6.72 ¢/kWh</td></tr>
<tr><td>Dallas</td><td>5.57 ¢/kWh</td></tr>
<tr><td rowspan="6">Water/Wastewater Rates</td><td colspan="2">The water and wastewater rates were taken from a paper from the US DOE (Bunch et al., 2017).</td></tr>
<tr><td>Chicago</td><td>8$/1000 gal</td></tr>
<tr><td>San Jose</td><td>8$/1000 gal</td></tr>
<tr><td>Salt Lake City</td><td>6.5$/1000 gal</td></tr>
<tr><td>Washington DC</td><td>7$/1000 gal</td></tr>
<tr><td>Dallas</td><td>6$/1000 gal</td></tr>
</table>

5.3.2 LCC Results

The results of all the life cycle cost are summarized in Table 5-5. The configurations that provided the least amount of savings are formatted to turn red and the configurations that saved the most money are formatted to turn green. The analysis concluded that the parameters which optimized the energy use did not always provide the best LCC. Resultantly, using a smaller range was never cost effective. This is because the cost to increase the pipe size, for lower ranges, was not restored by the small energy savings acquired at the energy optimized range. The most cost-effective range, for every location, was 6° C. The worst cost performing range, for each location, was near 3° C. Additionally, the heat exchanger's size made very little difference in the total cost savings. San Jose was the only location which exhibited a benefit to using a smaller heat exchanger. This is because the flat duration curve of San Jose's wet-bulb hours, as shown in Figure 4-1, allowed for a larger portion of economizing hours to be added as the approach was decreased, when compared to the other locations. The cooling tower approach that optimized cost savings was 0.5° C, for San Jose and Chicago, and 1.0° C, for Dallas, Washington D.C., and Salt Lake City. The LCC performance, of these lower approach cooling towers, demonstrated that oversizing the cooling towers not only saved energy, but also improved LCC. However, if the cooling tower is required to be installed on a roof, the extra footprint, and structural costs, may decrease the savings in some situations.

Table 5-5: LCC results

Design Parameters (^oC)			15-Year LCC Savings ($M)				
Range	CT Approach	HX Approach	Chicago	San Jose	Salt Lake	DC	Dallas
3	0.5	0.5	4.55	10.98	5.70	5.26	1.68
		1	4.61	10.63	5.68	5.33	1.72
		1.5	4.48	10.05	5.50	5.24	1.59
	1	0.5	4.42	10.28	5.69	4.85	1.50
		1	4.48	9.83	5.69	4.93	1.55
		1.5	4.38	8.98	5.51	4.82	1.45
	2	0.5	3.71	8.05	5.11	4.03	0.80
		1	3.80	7.40	5.10	4.08	0.85
		1.5	3.68	6.63	4.91	3.95	0.74
	3	0.5	2.88	5.40	4.43	2.91	-0.16
		1	2.93	4.90	4.41	2.91	-0.08
		1.5	2.81	4.32	4.21	2.79	-0.17
4	0.5	0.5	5.33	11.97	6.41	5.95	2.91
		1	5.42	11.73	6.44	6.05	2.99
		1.5	5.34	11.26	6.32	5.99	2.89
	1	0.5	5.29	11.47	6.47	5.82	2.97
		1	5.38	11.15	6.51	5.93	3.06
		1.5	5.32	10.46	6.39	5.86	2.98
	2	0.5	4.82	9.68	6.08	5.19	2.28
		1	4.93	9.14	6.12	5.28	2.37
		1.5	4.85	8.47	5.98	5.18	2.28
	3	0.5	4.13	7.41	5.55	4.33	1.51
		1	4.22	7.04	5.58	4.38	1.61
		1.5	4.12	6.48	5.43	4.27	1.54
5	0.5	0.5	5.71	12.26	6.60	6.36	3.64
		1	5.83	12.08	6.66	6.50	3.75
		1.5	5.77	11.68	6.57	6.47	3.69
	1	0.5	5.64	11.93	6.53	6.25	3.54
		1	5.76	11.69	6.61	6.39	3.66
		1.5	5.71	11.11	6.51	6.34	3.60
	2	0.5	5.27	10.29	6.38	5.73	3.09
		1	5.42	9.87	6.46	5.85	3.21
		1.5	5.36	9.33	6.36	5.78	3.14
	3	0.5	4.69	8.22	5.96	4.92	2.43
		1	4.81	7.99	6.04	5.00	2.55
		1.5	4.74	7.52	5.93	4.91	2.49
6	0.5	0.5	6.07	12.35	6.68	6.52	3.93
		1	6.20	12.17	6.77	6.67	4.06
		1.5	6.16	11.79	6.70	6.65	4.01
	1	0.5	5.89	12.02	6.72	6.58	3.95
		1	6.04	11.76	6.81	6.73	4.09
		1.5	6.01	11.23	6.74	6.69	4.05
	2	0.5	5.51	10.54	6.64	5.95	3.44
		1	5.67	10.17	6.72	6.08	3.57
		1.5	5.63	9.68	6.64	6.03	3.54
	3	0.5	4.98	8.64	6.15	5.29	2.90
		1	5.12	8.42	6.24	5.40	3.05
		1.5	5.08	8.03	6.15	5.34	3.02

Using the corresponding energy use, for the parameters that brought the best LCC per location, Figure 5-11 was remade but with the addition of the results of the most cost-efficient parameters. The "Typical WSE" is the baseline model, plus a 3° C approach cooling tower with an added 1.5° C approach heat exchanger. The "Energy Optimized WSE" is the configuration that used the least amount of energy per location. The "Cost Optimized WSE" is the configuration that had the lowest fifteen-year LCC. The results, shown in Figure 5-15 and Table 5-6, still show a large potential for energy savings of cost optimized waterside economizers in liquid-cooled data centers.

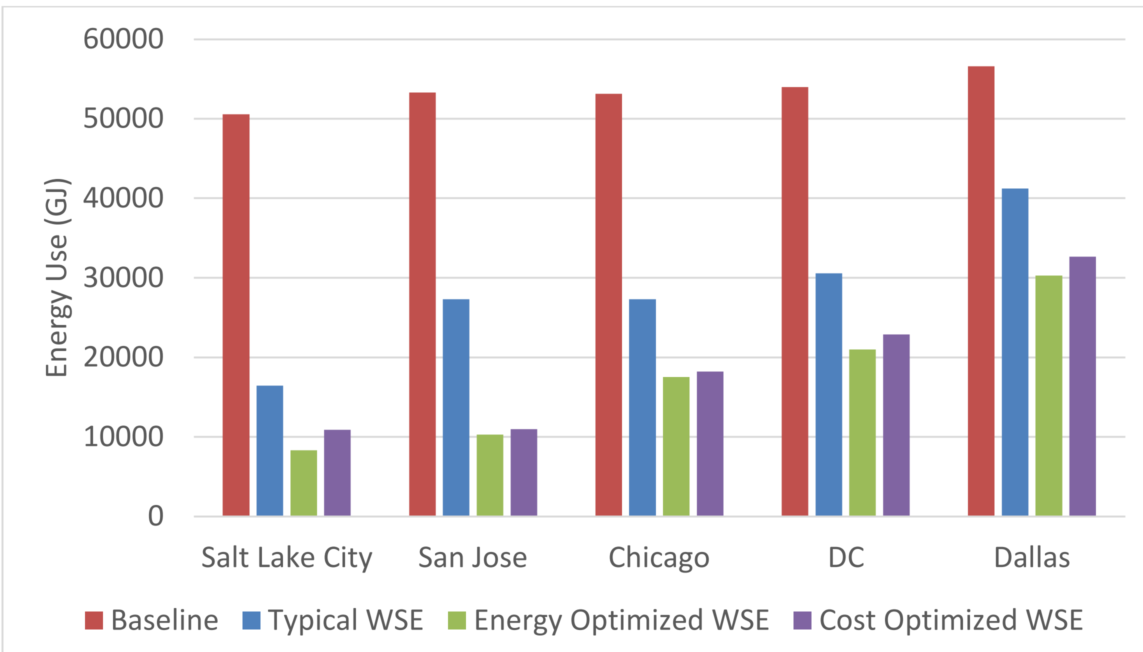


Figure 5-15: Energy use of energy and cost optimized WSE designs

Table 5-6: Waterside economizer percent annual energy savings versus baseline system

Percent Annual Energy Savings vs Baseline System			
Location	Typical WSE	Energy Optimized WSE	Cost Optimized WSE
Salt Lake City	67.49%	83.56%	78.44%
San Jose	48.75%	80.70%	79.44%
Chicago	48.57%	67.00%	65.69%
DC	43.38%	61.13%	57.59%
Dallas	27.15%	46.48%	42.27%

5.3.3 An Alternative Waterside Economizer Design Approach

For two of the studied locations, San Jose and Salt Lake City, full mechanical cooling was never required during the annual simulation. In other words, during the most humid time of the year, the system was still in partial economizing. In these cases, where no full mechanical cooling is required, it is recommended that the heat exchanger becomes part of the "mission critical" design. When the heat exchanger becomes mission critical, the chiller's size can be reduced because some of the design load is eliminated by partial economizing. However, another heat exchanger is required for redundancy as this component is now mission critical status as shown in Figure 5-16.

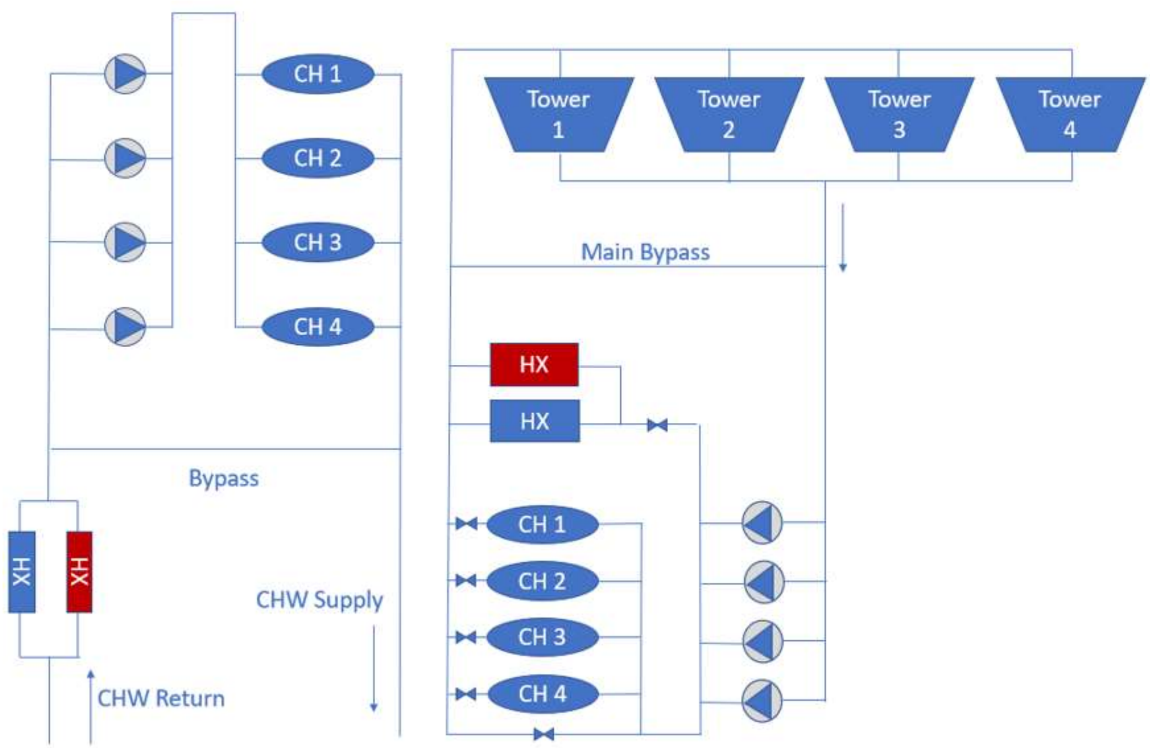


Figure 5-16: Alternative mission critical WSE design configuration

To further demonstrate this concept, a cost analysis of two different scenarios was completed. The first is the typical waterside economizer design as presented in this study, where the heat exchanger is not mission critical. This “typical” design’s parameters are a range of 6° C, cooling tower approach of 1° C, and a heat exchanger approach of 1° C. The second “alternative” design is with the heat exchanger as a mission critical component. This alternative design will have a range of 6° C, a cooling approach of 1° C, and two heat exchangers which will each have an approach of 1.5° C. Both these designs were simulated in EnergyPlus for San Jose and Salt Lake City.

The main benefit of adding the heat exchanger to “mission essential” is a reduced design chiller size. For the typical waterside economizer design, the total size requirement of the chillers, including the redundant chiller, is 4380 tons for San Jose and 4288 tons for Salt Lake City. If a 1.5 C° degree heat exchanger is added as mission critical, the total size requirement for the chillers is reduced as shown in Table 5-7. The reduced chiller size will save on initial capital cost. However, because the heat exchanger is now a mission critical component, there will be additional heat exchanger cost to convert from one to two heat exchangers. Even with the additional heat exchanger costs, there will still significant initial cost savings to justify the design for both San Jose and Salt Lake City. Lastly, the EnergyPlus simulation showed a small decrease in LCC due to the increase in total area of the heat exchanger in the alternative design. Adding the costs on these components up shows that the alternative design should be used in locations where the chilled water system can stay in economizing mode year-round.

Table 5-7: Alternative WSE design cost savings

	Traditional WSE Chiller Size	Alternative WSE Chiller Size	Initial Chiller Savings (RSMeans, 2020)	Additional Heat Exchanger Cost (Hewitt & Pugh, 2007)	Present Value of 15 Year Utility Savings
San Jose	4380 tons	3400 tons	$457K	$74K	$70K
Salt Lake City	4288 tons	2540 tons	$816K	$74K	$72K

Chapter 6

Conclusion

6.1 Summary

In this research, a parametric modeling study was completed for a liquid-cooled data center with a waterside economizer. The class W1 data center was simulated with a chilled water setpoint of 16.66° C (62° F). The study was carried out for five US locations, that are popular for data centers, including Chicago, Salt Lake City, San Jose, Washington DC, and Dallas. The study found that a waterside economizer does a great job at complementing a liquid-cooled data center by decreasing energy use and substantially decreasing fifteen-year LCC.

The energy analysis showed that increasing the size of waterside economizer components, including the heat exchanger and cooling tower, can significantly reduce energy use compared to a waterside economizer design as recommended by current literature. It was also confirmed that increasing the size of the cooling tower is better than increasing the size of the heat exchanger because of the summer energy savings with cooler condenser water for chillers. Additionally, using a decreased range in less humid locations yields overall energy savings. Furthermore, in the driest locations, like Salt Lake City and San Jose, increasing waterside economizer component sizes can eliminate the need for full mechanical cooling. Using a design, that does not require full mechanical cooling will allow the chiller's size to be decreased and the capital cost of the chillers will be reduced. Lastly, a location's number of WBDD_16.7 were compared with each location's optimized energy use, economizing hours, and optimized operating range. These linear relationships could provide an accurate estimate of waterside economizer performance for data centers which fall within the WBDD range covered by the locations in this paper.

The life cycle cost analysis showed that the optimized energy results did not exactly match the optimized cost results. In fact, in all locations, it was never cost effective to use a range smaller than 6° C. The optimized cooling tower approach was 0.5° C for San Jose and Chicago and the optimized cool tower approach was 1.0° C for all the other locations tested. Additionally, the size of the heat exchanger ended up not making a big enough difference to the fifteen-year LCC to justify a recommendation of one size of the heat exchanger over another. Overall, even when accounting for the cost of components, optimizing the design still presented significant cost and energy savings when compared to the baseline, or typical waterside economizer design, as shown in Figure 5-15. Lastly, an alternative design approach was shown to have even more cost savings by making the heat exchanger a mission critical component of the chilled water system.

6.2 Future Work

Ideas for future work on waterside economizers and data centers include:

- Evaluating how various ITE daily load profiles, and other chilled water setpoints, perform with waterside economizing. A flat load profile was used for this research, however there are many other common load profiles for data centers that can be scheduled into EnergyPlus.
- Exploring recommended cooling tower fan power limits, as expressed in ASHRAE 90.1, to find if further increasing the fan motor size will provide any benefits.
- Simulating a waterside economizer coupled with condenser water storage system to eliminate, or minimize, mechanical cooling and provide load shaping benefits.
- Further exploring the relationships of WBDD using different reference temperatures, load profiles, and data center classes.

- Analyzing and optimizing chiller performance during partial economizing to find minimum energy use controls and configurations.
- Deriving a new chiller performance model that includes a wider range of condenser water and chilled water supply temperatures. This model would be helpful for the higher chilled water setpoints of data centers and buildings using chilled beams or radiant cooling.

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Appendix A

Parametric Study Simulated Parameters by Location

Tables begin on next page

A.1 Chicago

Units key: Power (W), Temperature (^oC), Flow rate (m^3/s), Pressure (Pa), Length (m), UA (W/K)										
Range	CT approach	HX UA	Chiller size	CWS Temp	Fan power	CW pump flow	CW pump head	CW Pipe Size	CT air flow	CT UA
3	0.50	29,540,000	4,230,000	26.10	95,000	0.32	153,000	0.64	374	1,010,000
3	0.50	14,770,000	4,230,000	26.10	95,000	0.32	153,000	0.64	374	1,010,000
3	0.50	9,846,000	4,230,000	26.10	95,000	0.32	153,000	0.64	374	1,010,000
3	1.00	29,540,000	4,286,000	26.60	95,000	0.32	153,000	0.64	374	635,470
3	1.00	14,770,000	4,286,000	26.60	95,000	0.32	153,000	0.64	374	635,470
3	1.00	9,846,000	4,286,000	26.60	95,000	0.32	153,000	0.64	374	635,470
3	2.00	29,540,000	4,408,000	27.60	95,000	0.32	153,000	0.64	374	371,078
3	2.00	14,770,000	4,408,000	27.60	95,000	0.32	153,000	0.64	374	371,078
3	2.00	9,846,000	4,408,000	27.60	95,000	0.32	153,000	0.64	374	371,078
3	3.00	29,540,000	4,547,000	28.60	95,000	0.32	153,000	0.64	374	263,315
3	3.00	14,770,000	4,547,000	28.60	95,000	0.32	153,000	0.64	374	263,315
3	3.00	9,846,000	4,547,000	28.60	95,000	0.32	153,000	0.64	374	263,315
4	0.50	29,540,000	4,230,000	26.10	71,500	0.24	136,000	0.57	280	866,107
4	0.50	14,770,000	4,230,000	26.10	71,500	0.24	136,000	0.57	280	866,107
4	0.50	9,846,000	4,230,000	26.10	71,500	0.24	136,000	0.57	280	866,107
4	1.00	29,540,000	4,286,000	26.60	71,500	0.24	136,000	0.57	280	576,906
4	1.00	14,770,000	4,286,000	26.60	71,500	0.24	136,000	0.57	280	576,906
4	1.00	9,846,000	4,286,000	26.60	71,500	0.24	136,000	0.57	280	576,906
4	2.00	29,540,000	4,408,000	27.60	71,500	0.24	136,000	0.57	280	347,578
4	2.00	14,770,000	4,408,000	27.60	71,500	0.24	136,000	0.57	280	347,578
4	2.00	9,846,000	4,408,000	27.60	71,500	0.24	136,000	0.57	280	347,578
4	3.00	29,540,000	4,547,000	28.60	71,500	0.24	136,000	0.57	280	250,347
4	3.00	14,770,000	4,547,000	28.60	71,500	0.24	136,000	0.57	280	250,347
4	3.00	9,846,000	4,547,000	28.60	71,500	0.24	136,000	0.57	280	250,347
5	0.50	29,540,000	4,230,000	26.10	57,000	0.19	122,000	0.53	224	784,300
5	0.50	14,770,000	4,230,000	26.10	57,000	0.19	122,000	0.53	224	784,300
5	0.50	9,846,000	4,230,000	26.10	57,000	0.19	122,000	0.53	224	784,300
5	1.00	29,540,000	4,286,000	26.60	57,000	0.19	122,000	0.53	224	524,955
5	1.00	14,770,000	4,286,000	26.60	57,000	0.19	122,000	0.53	224	524,955
5	1.00	9,846,000	4,286,000	26.60	57,000	0.19	122,000	0.53	224	524,955
5	2.00	29,540,000	4,408,000	27.60	57,000	0.19	122,000	0.53	224	324,896
5	2.00	14,770,000	4,408,000	27.60	57,000	0.19	122,000	0.53	224	324,896
5	2.00	9,846,000	4,408,000	27.60	57,000	0.19	122,000	0.53	224	324,896
5	3.00	29,540,000	4,547,000	28.60	57,000	0.19	122,000	0.53	224	237,210
5	3.00	14,770,000	4,547,000	28.60	57,000	0.19	122,000	0.53	224	237,210
5	3.00	9,846,000	4,547,000	28.60	57,000	0.19	122,000	0.53	224	237,210
6	0.50	29,540,000	4,230,000	26.10	47,500	0.16	122,000	0.49	187	700,356
6	0.50	14,770,000	4,230,000	26.10	47,500	0.16	122,000	0.49	187	700,356
6	0.50	9,846,000	4,230,000	26.10	47,500	0.16	122,000	0.49	187	700,356
6	1.00	29,540,000	4,286,000	26.60	47,500	0.16	122,000	0.49	187	479,552
6	1.00	14,770,000	4,286,000	26.60	47,500	0.16	122,000	0.49	187	479,552
6	1.00	9,846,000	4,286,000	26.60	47,500	0.16	122,000	0.49	187	479,552
6	2.00	29,540,000	4,408,000	27.60	47,500	0.16	122,000	0.49	187	303,794
6	2.00	14,770,000	4,408,000	27.60	47,500	0.16	122,000	0.49	187	303,794
6	2.00	9,846,000	4,408,000	27.60	47,500	0.16	122,000	0.49	187	303,794
6	3.00	29,540,000	4,547,000	28.60	47,500	0.16	122,000	0.49	187	224,559
6	3.00	14,770,000	4,547,000	28.60	47,500	0.16	122,000	0.49	187	224,559
6	3.00	9,846,000	4,547,000	28.60	47,500	0.16	122,000	0.49	187	224,559

A.2 Dallas

Units key: Power (W), Temperature (^oC), Flow rate (m^3/s), Pressure (Pa), Length (m), UA (W/K)										
Range	CT approach	HX UA	Chiller size	CWS Temp	Fan power	CW pump flow	CW pump head	CW Pipe Size	CT air flow	CT UA
3	0.50	29,540,000	4,256,000	26.33	95,000	0.32	153,000	0.64	364	990,680
3	0.50	14,770,000	4,256,000	26.33	95,000	0.32	153,000	0.64	364	990,680
3	0.50	9,846,000	4,256,000	26.33	95,000	0.32	153,000	0.64	364	990,680
3	1.00	29,540,000	4,313,000	26.83	95,000	0.32	153,000	0.64	364	620,648
3	1.00	14,770,000	4,313,000	26.83	95,000	0.32	153,000	0.64	364	620,648
3	1.00	9,846,000	4,313,000	26.83	95,000	0.32	153,000	0.64	364	620,648
3	2.00	29,540,000	4,439,000	27.83	95,000	0.32	153,000	0.64	364	361,166
3	2.00	14,770,000	4,439,000	27.83	95,000	0.32	153,000	0.64	364	361,166
3	2.00	9,846,000	4,439,000	27.83	95,000	0.32	153,000	0.64	364	361,166
3	3.00	29,540,000	4,581,000	28.83	95,000	0.32	153,000	0.64	364	255,873
3	3.00	14,770,000	4,581,000	28.83	95,000	0.32	153,000	0.64	364	255,873
3	3.00	9,846,000	4,581,000	28.83	95,000	0.32	153,000	0.64	364	255,873
4	0.50	29,540,000	4,256,000	26.33	71,500	0.24	136,000	0.57	273	873,227
4	0.50	14,770,000	4,256,000	26.33	71,500	0.24	136,000	0.57	273	873,227
4	0.50	9,846,000	4,256,000	26.33	71,500	0.24	136,000	0.57	273	873,227
4	1.00	29,540,000	4,313,000	26.83	71,500	0.24	136,000	0.57	273	566,012
4	1.00	14,770,000	4,313,000	26.83	71,500	0.24	136,000	0.57	273	566,012
4	1.00	9,846,000	4,313,000	26.83	71,500	0.24	136,000	0.57	273	566,012
4	2.00	29,540,000	4,439,000	27.83	71,500	0.24	136,000	0.57	273	339,607
4	2.00	14,770,000	4,439,000	27.83	71,500	0.24	136,000	0.57	273	339,607
4	2.00	9,846,000	4,439,000	27.83	71,500	0.24	136,000	0.57	273	339,607
4	3.00	29,540,000	4,581,000	28.83	71,500	0.24	136,000	0.57	273	244,112
4	3.00	14,770,000	4,581,000	28.83	71,500	0.24	136,000	0.57	273	244,112
4	3.00	9,846,000	4,581,000	28.83	71,500	0.24	136,000	0.57	273	244,112
5	0.50	29,540,000	4,256,000	26.33	57,000	0.19	122,000	0.53	218	774,716
5	0.50	14,770,000	4,256,000	26.33	57,000	0.19	122,000	0.53	218	774,716
5	0.50	9,846,000	4,256,000	26.33	57,000	0.19	122,000	0.53	218	774,716
5	1.00	29,540,000	4,313,000	26.83	57,000	0.19	122,000	0.53	218	516,272
5	1.00	14,770,000	4,313,000	26.83	57,000	0.19	122,000	0.53	218	516,272
5	1.00	9,846,000	4,313,000	26.83	57,000	0.19	122,000	0.53	218	516,272
5	2.00	29,540,000	4,439,000	27.83	57,000	0.19	122,000	0.53	218	318,132
5	2.00	14,770,000	4,439,000	27.83	57,000	0.19	122,000	0.53	218	318,132
5	2.00	9,846,000	4,439,000	27.83	57,000	0.19	122,000	0.53	218	318,132
5	3.00	29,540,000	4,581,000	28.83	57,000	0.19	122,000	0.53	218	231,751
5	3.00	14,770,000	4,581,000	28.83	57,000	0.19	122,000	0.53	218	231,751
5	3.00	9,846,000	4,581,000	28.83	57,000	0.19	122,000	0.53	218	231,751
6	0.50	29,540,000	4,256,000	26.33	47,500	0.16	122,000	0.49	182	692,550
6	0.50	14,770,000	4,256,000	26.33	47,500	0.16	122,000	0.49	182	692,550
6	0.50	9,846,000	4,256,000	26.33	47,500	0.16	122,000	0.49	182	692,550
6	1.00	29,540,000	4,313,000	26.83	47,500	0.16	122,000	0.49	182	472,229
6	1.00	14,770,000	4,313,000	26.83	47,500	0.16	122,000	0.49	182	472,229
6	1.00	9,846,000	4,313,000	26.83	47,500	0.16	122,000	0.49	182	472,229
6	2.00	29,540,000	4,439,000	27.83	47,500	0.16	122,000	0.49	182	297,853
6	2.00	14,770,000	4,439,000	27.83	47,500	0.16	122,000	0.49	182	297,853
6	2.00	9,846,000	4,439,000	27.83	47,500	0.16	122,000	0.49	182	297,853
6	3.00	29,540,000	4,581,000	28.83	47,500	0.16	122,000	0.49	182	219,651
6	3.00	14,770,000	4,581,000	28.83	47,500	0.16	122,000	0.49	182	219,651
6	3.00	9,846,000	4,581,000	28.83	47,500	0.16	122,000	0.49	182	219,651

A.3 Salt Lake City

Units key: Power (W), Temperature (^oC), Flow rate (m^3/s), Pressure (Pa), Length (m), UA (W/K)										
Range	CT approach	HX UA	Chiller size	CWS Temp	Fan power	CW pump flow	CW pump head	CW Pipe Size	CT air flow	CT UA
3	0.50	29,540,000	3,749,000	19.50	94,400	0.32	153,000	0.64	319	1,978,000
3	0.50	14,770,000	3,749,000	19.50	94,400	0.32	153,000	0.64	319	1,978,000
3	0.50	9,846,000	3,749,000	19.50	94,400	0.32	153,000	0.64	319	1,978,000
3	1.00	29,540,000	3,772,000	20.00	94,400	0.32	153,000	0.64	319	986,296
3	1.00	14,770,000	3,772,000	20.00	94,400	0.32	153,000	0.64	319	986,296
3	1.00	9,846,000	3,772,000	20.00	94,400	0.32	153,000	0.64	319	986,296
3	2.00	29,540,000	3,824,000	21.00	94,400	0.32	153,000	0.64	319	492,997
3	2.00	14,770,000	3,824,000	21.00	94,400	0.32	153,000	0.64	319	492,997
3	2.00	9,846,000	3,824,000	21.00	94,400	0.32	153,000	0.64	319	492,997
3	3.00	29,540,000	3,884,000	22.00	94,400	0.32	153,000	0.64	319	328,950
3	3.00	14,770,000	3,884,000	22.00	94,400	0.32	153,000	0.64	319	328,950
3	3.00	9,846,000	3,884,000	22.00	94,400	0.32	153,000	0.64	319	328,950
4	0.50	29,540,000	3,749,000	19.50	70,800	0.24	136,000	0.57	239	1,870,000
4	0.50	14,770,000	3,749,000	19.50	70,800	0.24	136,000	0.57	239	1,870,000
4	0.50	9,846,000	3,749,000	19.50	70,800	0.24	136,000	0.57	239	1,870,000
4	1.00	29,540,000	3,772,000	20.00	70,800	0.24	136,000	0.57	239	952,204
4	1.00	14,770,000	3,772,000	20.00	70,800	0.24	136,000	0.57	239	952,204
4	1.00	9,846,000	3,772,000	20.00	70,800	0.24	136,000	0.57	239	952,204
4	2.00	29,540,000	3,824,000	21.00	70,800	0.24	136,000	0.57	239	481,084
4	2.00	14,770,000	3,824,000	21.00	70,800	0.24	136,000	0.57	239	481,084
4	2.00	9,846,000	3,824,000	21.00	70,800	0.24	136,000	0.57	239	481,084
4	3.00	29,540,000	3,884,000	22.00	70,800	0.24	136,000	0.57	239	322,163
4	3.00	14,770,000	3,884,000	22.00	70,800	0.24	136,000	0.57	239	322,163
4	3.00	9,846,000	3,884,000	22.00	70,800	0.24	136,000	0.57	239	322,163
5	0.50	29,540,000	3,749,000	19.50	56,600	0.19	122,000	0.53	191	1,703,000
5	0.50	14,770,000	3,749,000	19.50	56,600	0.19	122,000	0.53	191	1,703,000
5	0.50	9,846,000	3,749,000	19.50	56,600	0.19	122,000	0.53	191	1,703,000
5	1.00	29,540,000	3,772,000	20.00	56,600	0.19	122,000	0.53	191	898,835
5	1.00	14,770,000	3,772,000	20.00	56,600	0.19	122,000	0.53	191	898,835
5	1.00	9,846,000	3,772,000	20.00	56,600	0.19	122,000	0.53	191	898,835
5	2.00	29,540,000	3,824,000	21.00	56,600	0.19	122,000	0.53	191	463,033
5	2.00	14,770,000	3,824,000	21.00	56,600	0.19	122,000	0.53	191	463,033
5	2.00	9,846,000	3,824,000	21.00	56,600	0.19	122,000	0.53	191	463,033
5	3.00	29,540,000	3,884,000	22.00	56,600	0.19	122,000	0.53	191	312,178
5	3.00	14,770,000	3,884,000	22.00	56,600	0.19	122,000	0.53	191	312,178
5	3.00	9,846,000	3,884,000	22.00	56,600	0.19	122,000	0.53	191	312,178
6	0.50	29,540,000	3,749,000	19.50	47,200	0.16	122,000	0.49	159	1,520,000
6	0.50	14,770,000	3,749,000	19.50	47,200	0.16	122,000	0.49	159	1,520,000
6	0.50	9,846,000	3,749,000	19.50	47,200	0.16	122,000	0.49	159	1,520,000
6	1.00	29,540,000	3,772,000	20.00	47,200	0.16	122,000	0.49	159	835,874
6	1.00	14,770,000	3,772,000	20.00	47,200	0.16	122,000	0.49	159	835,874
6	1.00	9,846,000	3,772,000	20.00	47,200	0.16	122,000	0.49	159	835,874
6	2.00	29,540,000	3,824,000	21.00	47,200	0.16	122,000	0.49	159	441,476
6	2.00	14,770,000	3,824,000	21.00	47,200	0.16	122,000	0.49	159	441,476
6	2.00	9,846,000	3,824,000	21.00	47,200	0.16	122,000	0.49	159	441,476
6	3.00	29,540,000	3,884,000	22.00	47,200	0.16	122,000	0.49	159	300,368
6	3.00	14,770,000	3,884,000	22.00	47,200	0.16	122,000	0.49	159	300,368
6	3.00	9,846,000	3,884,000	22.00	47,200	0.16	122,000	0.49	159	300,368

A.4 San Jose

Units key: Power (W), Temperature (^oC), Flow rate (m^3/s), Pressure (Pa), Length (m), UA (W/K)										
Range	CT approach	HX UA	Chiller size	CWS Temp	Fan power	CW pump flow	CW pump head	CW Pipe Size	CT air flow	CT UA
3	0.50	29,540,000	3,824,000	21.00	94,500	0.32	153,000	0.64	373	1,449,000
3	0.50	14,770,000	3,824,000	21.00	94,500	0.32	153,000	0.64	373	1,449,000
3	0.50	9,846,000	3,824,000	21.00	94,500	0.32	153,000	0.64	373	1,449,000
3	1.00	29,540,000	3,853,000	21.50	94,500	0.32	153,000	0.64	373	859,039
3	1.00	14,770,000	3,853,000	21.50	94,500	0.32	153,000	0.64	373	859,039
3	1.00	9,846,000	3,853,000	21.50	94,500	0.32	153,000	0.64	373	859,039
3	2.00	29,540,000	3,917,000	22.50	94,500	0.32	153,000	0.64	373	478,029
3	2.00	14,770,000	3,917,000	22.50	94,500	0.32	153,000	0.64	373	478,029
3	2.00	9,846,000	3,917,000	22.50	94,500	0.32	153,000	0.64	373	478,029
3	3.00	29,540,000	3,990,000	23.50	94,500	0.32	153,000	0.64	373	332,037
3	3.00	14,770,000	3,990,000	23.50	94,500	0.32	153,000	0.64	373	332,037
3	3.00	9,846,000	3,990,000	23.50	94,500	0.32	153,000	0.64	373	332,037
4	0.50	29,540,000	3,824,000	21.00	71,000	0.24	136,000	0.57	280	1,305,000
4	0.50	14,770,000	3,824,000	21.00	71,000	0.24	136,000	0.57	280	1,305,000
4	0.50	9,846,000	3,824,000	21.00	71,000	0.24	136,000	0.57	280	1,305,000
4	1.00	29,540,000	3,853,000	21.50	71,000	0.24	136,000	0.57	280	799,705
4	1.00	14,770,000	3,853,000	21.50	71,000	0.24	136,000	0.57	280	799,705
4	1.00	9,846,000	3,853,000	21.50	71,000	0.24	136,000	0.57	280	799,705
4	2.00	29,540,000	3,917,000	22.50	71,000	0.24	136,000	0.57	280	456,777
4	2.00	14,770,000	3,917,000	22.50	71,000	0.24	136,000	0.57	280	456,777
4	2.00	9,846,000	3,917,000	22.50	71,000	0.24	136,000	0.57	280	456,777
4	3.00	29,540,000	3,990,000	23.50	71,000	0.24	136,000	0.57	280	320,864
4	3.00	14,770,000	3,990,000	23.50	71,000	0.24	136,000	0.57	280	320,864
4	3.00	9,846,000	3,990,000	23.50	71,000	0.24	136,000	0.57	280	320,864
5	0.50	29,540,000	3,824,000	21.00	56,700	0.19	122,000	0.53	224	1,170,000
5	0.50	14,770,000	3,824,000	21.00	56,700	0.19	122,000	0.53	224	1,170,000
5	0.50	9,846,000	3,824,000	21.00	56,700	0.19	122,000	0.53	224	1,170,000
5	1.00	29,540,000	3,853,000	21.50	56,700	0.19	122,000	0.53	224	738,810
5	1.00	14,770,000	3,853,000	21.50	56,700	0.19	122,000	0.53	224	738,810
5	1.00	9,846,000	3,853,000	21.50	56,700	0.19	122,000	0.53	224	738,810
5	2.00	29,540,000	3,917,000	22.50	56,700	0.19	122,000	0.53	224	432,816
5	2.00	14,770,000	3,917,000	22.50	56,700	0.19	122,000	0.53	224	432,816
5	2.00	9,846,000	3,917,000	22.50	56,700	0.19	122,000	0.53	224	432,816
5	3.00	29,540,000	3,990,000	23.50	56,700	0.19	122,000	0.53	224	307,549
5	3.00	14,770,000	3,990,000	23.50	56,700	0.19	122,000	0.53	224	307,549
5	3.00	9,846,000	3,990,000	23.50	56,700	0.19	122,000	0.53	224	307,549
6	0.50	29,540,000	3,824,000	21.00	47,250	0.16	122,000	0.49	187	1,050,000
6	0.50	14,770,000	3,824,000	21.00	47,250	0.16	122,000	0.49	187	1,050,000
6	0.50	9,846,000	3,824,000	21.00	47,250	0.16	122,000	0.49	187	1,050,000
6	1.00	29,540,000	3,853,000	21.50	47,250	0.16	122,000	0.49	187	680,868
6	1.00	14,770,000	3,853,000	21.50	47,250	0.16	122,000	0.49	187	680,868
6	1.00	9,846,000	3,853,000	21.50	47,250	0.16	122,000	0.49	187	680,868
6	2.00	29,540,000	3,917,000	22.50	47,250	0.16	122,000	0.49	187	408,500
6	2.00	14,770,000	3,917,000	22.50	47,250	0.16	122,000	0.49	187	408,500
6	2.00	9,846,000	3,917,000	22.50	47,250	0.16	122,000	0.49	187	408,500
6	3.00	29,540,000	3,990,000	23.50	47,250	0.16	122,000	0.49	187	293,595
6	3.00	14,770,000	3,990,000	23.50	47,250	0.16	122,000	0.49	187	293,595
6	3.00	9,846,000	3,990,000	23.50	47,250	0.16	122,000	0.49	187	293,595

A.5 Washington DC

Units key: Power (W), Temperature (^oC), Flow rate (m^3/s), Pressure (Pa), Length (m), UA (W/K)										
Range	CT approach	HX UA	Chiller size	CWS Temp	Fan power	CW pump flow	CW pump head	CW Pipe Size	CT air flow	CT UA
3	0.50	29,540,000	4,198,000	25.80	95,000	0.32	153,000	0.64	369	1,032,000
3	0.50	14,770,000	4,198,000	25.80	95,000	0.32	153,000	0.64	369	1,032,000
3	0.50	9,846,000	4,198,000	25.80	95,000	0.32	153,000	0.64	369	1,032,000
3	1.00	29,540,000	4,252,000	26.30	95,000	0.32	153,000	0.64	369	645,135
3	1.00	14,770,000	4,252,000	26.30	95,000	0.32	153,000	0.64	369	645,135
3	1.00	9,846,000	4,252,000	26.30	95,000	0.32	153,000	0.64	369	645,135
3	2.00	29,540,000	4,370,000	27.30	95,000	0.32	153,000	0.64	369	374,741
3	2.00	14,770,000	4,370,000	27.30	95,000	0.32	153,000	0.64	369	374,741
3	2.00	9,846,000	4,370,000	27.30	95,000	0.32	153,000	0.64	369	374,741
3	3.00	29,540,000	4,504,000	28.30	95,000	0.32	153,000	0.64	369	265,268
3	3.00	14,770,000	4,504,000	28.30	95,000	0.32	153,000	0.64	369	265,268
3	3.00	9,846,000	4,504,000	28.30	95,000	0.32	153,000	0.64	369	265,268
4	0.50	29,540,000	4,198,000	25.80	71,300	0.24	136,000	0.57	277	906,966
4	0.50	14,770,000	4,198,000	25.80	71,300	0.24	136,000	0.57	277	906,966
4	0.50	9,846,000	4,198,000	25.80	71,300	0.24	136,000	0.57	277	906,966
4	1.00	29,540,000	4,252,000	26.30	71,300	0.24	136,000	0.57	277	586,954
4	1.00	14,770,000	4,252,000	26.30	71,300	0.24	136,000	0.57	277	586,954
4	1.00	9,846,000	4,252,000	26.30	71,300	0.24	136,000	0.57	277	586,954
4	2.00	29,540,000	4,370,000	27.30	71,300	0.24	136,000	0.57	277	351,648
4	2.00	14,770,000	4,370,000	27.30	71,300	0.24	136,000	0.57	277	351,648
4	2.00	9,846,000	4,370,000	27.30	71,300	0.24	136,000	0.57	277	351,648
4	3.00	29,540,000	4,504,000	28.30	71,300	0.24	136,000	0.57	277	252,581
4	3.00	14,770,000	4,504,000	28.30	71,300	0.24	136,000	0.57	277	252,581
4	3.00	9,846,000	4,504,000	28.30	71,300	0.24	136,000	0.57	277	252,581
5	0.50	29,540,000	4,198,000	25.80	57,000	0.19	122,000	0.53	221	803,464
5	0.50	14,770,000	4,198,000	25.80	57,000	0.19	122,000	0.53	221	803,464
5	0.50	9,846,000	4,198,000	25.80	57,000	0.19	122,000	0.53	221	803,464
5	1.00	29,540,000	4,252,000	26.30	57,000	0.19	122,000	0.53	221	534,737
5	1.00	14,770,000	4,252,000	26.30	57,000	0.19	122,000	0.53	221	534,737
5	1.00	9,846,000	4,252,000	26.30	57,000	0.19	122,000	0.53	221	534,737
5	2.00	29,540,000	4,370,000	27.30	57,000	0.19	122,000	0.53	221	329,085
5	2.00	14,770,000	4,370,000	27.30	57,000	0.19	122,000	0.53	221	329,085
5	2.00	9,846,000	4,370,000	27.30	57,000	0.19	122,000	0.53	221	329,085
5	3.00	29,540,000	4,504,000	28.30	57,000	0.19	122,000	0.53	221	239,568
5	3.00	14,770,000	4,504,000	28.30	57,000	0.19	122,000	0.53	221	239,568
5	3.00	9,846,000	4,504,000	28.30	57,000	0.19	122,000	0.53	221	239,568
6	0.50	29,540,000	4,198,000	25.80	47,500	0.16	122,000	0.49	184	717,602
6	0.50	14,770,000	4,198,000	25.80	47,500	0.16	122,000	0.49	184	717,602
6	0.50	9,846,000	4,198,000	25.80	47,500	0.16	122,000	0.49	184	717,602
6	1.00	29,540,000	4,252,000	26.30	47,500	0.16	122,000	0.49	184	488,774
6	1.00	14,770,000	4,252,000	26.30	47,500	0.16	122,000	0.49	184	488,774
6	1.00	9,846,000	4,252,000	26.30	47,500	0.16	122,000	0.49	184	488,774
6	2.00	29,540,000	4,370,000	27.30	47,500	0.16	122,000	0.49	184	307,934
6	2.00	14,770,000	4,370,000	27.30	47,500	0.16	122,000	0.49	184	307,934
6	2.00	9,846,000	4,370,000	27.30	47,500	0.16	122,000	0.49	184	307,934
6	3.00	29,540,000	4,504,000	28.30	47,500	0.16	122,000	0.49	184	226,943
6	3.00	14,770,000	4,504,000	28.30	47,500	0.16	122,000	0.49	184	226,943
6	3.00	9,846,000	4,504,000	28.30	47,500	0.16	122,000	0.49	184	226,943

Appendix B

Life Cycle Cost Data

Tables begin on next page

B.1 Chicago

Parameters (°C)			Present Value ($K)					
HX Approach	CT Approach	Range	15-Year Electrical and Water	CT	HX	Pumps	Pipe & fittings	Total
0.5	0.5	3	10,475.0	1,421.0	507.8	50.0	111.0	12,564.9
1	0.5	3	10,668.3	1,421.0	253.9	50.0	111.0	12,504.2
1.5	0.5	3	10,881.5	1,421.0	169.3	50.0	111.0	12,632.7
0.5	1	3	10,928.2	1,101.0	507.8	50.0	111.0	12,698.0
1	1	3	11,119.4	1,101.0	253.9	50.0	111.0	12,635.3
1.5	1	3	11,300.6	1,101.0	169.3	50.0	111.0	12,731.8
0.5	2	3	11,869.6	862.0	507.8	50.0	111.0	13,400.4
1	2	3	12,042.4	862.0	253.9	50.0	111.0	13,319.3
1.5	2	3	12,246.9	862.0	169.3	50.0	111.0	13,439.1
0.5	3	3	12,919.1	645.0	507.8	50.0	111.0	14,233.0
1	3	3	13,124.5	645.0	253.9	50.0	111.0	14,184.4
1.5	3	3	13,325.0	645.0	169.3	50.0	111.0	14,300.3
0.5	0.5	4	9,845.5	1,343.0	507.8	30.0	60.0	11,786.3
1	0.5	4	10,008.7	1,343.0	253.9	30.0	60.0	11,695.6
1.5	0.5	4	10,173.6	1,343.0	169.3	30.0	60.0	11,775.9
0.5	1	4	10,207.1	1,022.0	507.8	30.0	60.0	11,826.9
1	1	4	10,365.0	1,022.0	253.9	30.0	60.0	11,730.9
1.5	1	4	10,513.2	1,022.0	169.3	30.0	60.0	11,794.4
0.5	2	4	10,985.9	708.0	507.8	30.0	60.0	12,291.7
1	2	4	11,129.2	708.0	253.9	30.0	60.0	12,181.1
1.5	2	4	11,296.9	708.0	169.3	30.0	60.0	12,264.2
0.5	3	4	11,850.8	537.0	507.8	30.0	60.0	12,985.7
1	3	4	12,014.6	537.0	253.9	30.0	60.0	12,895.5
1.5	3	4	12,199.6	537.0	169.3	30.0	60.0	12,995.9
0.5	0.5	5	9,608.9	1,255.0	507.8	10.0	26.0	11,407.8
1	0.5	5	9,742.0	1,255.0	253.9	10.0	26.0	11,286.9
1.5	0.5	5	9,885.4	1,255.0	169.3	10.0	26.0	11,345.7
0.5	1	5	9,952.3	980.0	507.8	10.0	26.0	11,476.1
1	1	5	10,082.0	980.0	253.9	10.0	26.0	11,351.9
1.5	1	5	10,214.8	980.0	169.3	10.0	26.0	11,400.1
0.5	2	5	10,637.0	660.0	507.8	10.0	26.0	11,840.9
1	2	5	10,748.3	660.0	253.9	10.0	26.0	11,698.2
1.5	2	5	10,892.9	660.0	169.3	10.0	26.0	11,758.2
0.5	3	5	11,371.8	505.0	507.8	10.0	26.0	12,420.7
1	3	5	11,506.2	505.0	253.9	10.0	26.0	12,301.1
1.5	3	5	11,662.6	505.0	169.3	10.0	26.0	12,372.9
0.5	0.5	6	9,523.4	1,012.0	507.8	0.0	0.0	11,043.3
1	0.5	6	9,652.2	1,012.0	253.9	0.0	0.0	10,918.1
1.5	0.5	6	9,771.1	1,012.0	169.3	0.0	0.0	10,952.3
0.5	1	6	9,869.4	845.0	507.8	0.0	0.0	11,222.2
1	1	6	9,972.4	845.0	253.9	0.0	0.0	11,071.4
1.5	1	6	10,085.7	845.0	169.3	0.0	0.0	11,099.9
0.5	2	6	10,497.6	595.0	507.8	0.0	0.0	11,600.4
1	2	6	10,600.0	595.0	253.9	0.0	0.0	11,448.9
1.5	2	6	10,720.3	595.0	169.3	0.0	0.0	11,484.6
0.5	3	6	11,178.9	450.0	507.8	0.0	0.0	12,136.7
1	3	6	11,289.3	450.0	253.9	0.0	0.0	11,993.2
1.5	3	6	11,416.1	450.0	169.3	0.0	0.0	12,035.3

B.2 Dallas

Parameters (°C)			Present Value ($K)					
HX Approach	CT Approach	Range	15-Year Electrical and Water	CT	HX	Pumps	Pipe & fittings	Total
0.5	0.5	3	13,266.3	1,700.0	507.8	50.0	111.0	15,635.2
1	0.5	3	13,477.8	1,700.0	253.9	50.0	111.0	15,592.7
1.5	0.5	3	13,692.1	1,700.0	169.3	50.0	111.0	15,722.3
0.5	1	3	13,851.5	1,292.0	507.8	50.0	111.0	15,812.3
1	1	3	14,053.3	1,292.0	253.9	50.0	111.0	15,760.2
1.5	1	3	14,244.0	1,292.0	169.3	50.0	111.0	15,866.3
0.5	2	3	14,962.1	887.0	507.8	50.0	111.0	16,517.9
1	2	3	15,161.0	887.0	253.9	50.0	111.0	16,462.9
1.5	2	3	15,358.3	887.0	169.3	50.0	111.0	16,575.6
0.5	3	3	16,085.4	717.0	507.8	50.0	111.0	17,471.2
1	3	3	16,265.8	717.0	253.9	50.0	111.0	17,397.8
1.5	3	3	16,434.7	717.0	169.3	50.0	111.0	17,482.0
0.5	0.5	4	12,207.0	1,604.0	507.8	30.0	60.0	14,408.8
1	0.5	4	12,378.9	1,604.0	253.9	30.0	60.0	14,326.8
1.5	0.5	4	12,558.2	1,604.0	169.3	30.0	60.0	14,421.5
0.5	1	4	12,695.6	1,047.0	507.8	30.0	60.0	14,340.5
1	1	4	12,862.7	1,047.0	253.9	30.0	60.0	14,253.6
1.5	1	4	13,024.1	1,047.0	169.3	30.0	60.0	14,330.3
0.5	2	4	13,632.7	805.0	507.8	30.0	60.0	15,035.5
1	2	4	13,799.3	805.0	253.9	30.0	60.0	14,948.2
1.5	2	4	13,971.3	805.0	169.3	30.0	60.0	15,035.5
0.5	3	4	14,594.4	609.0	507.8	30.0	60.0	15,801.2
1	3	4	14,747.8	609.0	253.9	30.0	60.0	15,700.7
1.5	3	4	14,904.6	609.0	169.3	30.0	60.0	15,772.9
0.5	0.5	5	11,724.5	1,406.0	507.8	10.0	26.0	13,674.3
1	0.5	5	11,871.4	1,406.0	253.9	10.0	26.0	13,567.4
1.5	0.5	5	12,016.7	1,406.0	169.3	10.0	26.0	13,627.9
0.5	1	5	12,160.4	1,070.0	507.8	10.0	26.0	13,774.2
1	1	5	12,294.7	1,070.0	253.9	10.0	26.0	13,654.6
1.5	1	5	12,438.0	1,070.0	169.3	10.0	26.0	13,713.3
0.5	2	5	12,980.1	699.0	507.8	10.0	26.0	14,223.0
1	2	5	13,114.9	699.0	253.9	10.0	26.0	14,103.8
1.5	2	5	13,266.1	699.0	169.3	10.0	26.0	14,170.4
0.5	3	5	13,824.0	521.0	507.8	10.0	26.0	14,888.8
1	3	5	13,953.0	521.0	253.9	10.0	26.0	14,763.9
1.5	3	5	14,093.3	521.0	169.3	10.0	26.0	14,819.5
0.5	0.5	6	11,470.1	1,404.0	507.8	0.0	0.0	13,381.9
1	0.5	6	11,600.5	1,404.0	253.9	0.0	0.0	13,258.4
1.5	0.5	6	11,728.3	1,404.0	169.3	0.0	0.0	13,301.6
0.5	1	6	11,888.2	972.0	507.8	0.0	0.0	13,368.0
1	1	6	11,997.4	972.0	253.9	0.0	0.0	13,223.3
1.5	1	6	12,123.6	972.0	169.3	0.0	0.0	13,264.8
0.5	2	6	12,647.4	717.0	507.8	0.0	0.0	13,872.2
1	2	6	12,771.0	717.0	253.9	0.0	0.0	13,741.9
1.5	2	6	12,888.0	717.0	169.3	0.0	0.0	13,774.3
0.5	3	6	13,435.6	470.0	507.8	0.0	0.0	14,413.4
1	3	6	13,540.0	470.0	253.9	0.0	0.0	14,263.9
1.5	3	6	13,656.7	470.0	169.3	0.0	0.0	14,295.9

B.3 Salt Lake City

Parameters (°C)			Present Value ($K)					
HX Approach	CT Approach	Range	15-Year Electrical and Water	CT	HX	Pumps	Pipe & fittings	Total
0.5	0.5	3	7,462.8	1,800.0	507.8	50.0	111.0	9,931.6
1	0.5	3	7,742.8	1,800.0	253.9	50.0	111.0	9,957.8
1.5	0.5	3	8,003.5	1,800.0	169.3	50.0	111.0	10,133.7
0.5	1	3	7,873.9	1,400.0	507.8	50.0	111.0	9,942.8
1	1	3	8,131.4	1,400.0	253.9	50.0	111.0	9,946.3
1.5	1	3	8,393.3	1,400.0	169.3	50.0	111.0	10,123.6
0.5	2	3	8,766.1	1,087.0	507.8	50.0	111.0	10,521.9
1	2	3	9,033.9	1,087.0	253.9	50.0	111.0	10,535.8
1.5	2	3	9,307.9	1,087.0	169.3	50.0	111.0	10,725.2
0.5	3	3	9,762.9	771.0	507.8	50.0	111.0	11,202.7
1	3	3	10,041.0	771.0	253.9	50.0	111.0	11,226.9
1.5	3	3	10,325.6	771.0	169.3	50.0	111.0	11,426.8
0.5	0.5	4	7,023.8	1,600.0	507.8	30.0	60.0	9,221.6
1	0.5	4	7,248.5	1,600.0	253.9	30.0	60.0	9,192.4
1.5	0.5	4	7,458.5	1,600.0	169.3	30.0	60.0	9,317.7
0.5	1	4	7,327.1	1,242.0	507.8	30.0	60.0	9,166.9
1	1	4	7,536.0	1,242.0	253.9	30.0	60.0	9,121.9
1.5	1	4	7,743.6	1,242.0	169.3	30.0	60.0	9,244.9
0.5	2	4	8,002.6	954.0	507.8	30.0	60.0	9,554.5
1	2	4	8,218.3	954.0	253.9	30.0	60.0	9,516.2
1.5	2	4	8,438.3	954.0	169.3	30.0	60.0	9,651.6
0.5	3	4	8,772.6	710.0	507.8	30.0	60.0	10,080.4
1	3	4	8,999.9	710.0	253.9	30.0	60.0	10,053.8
1.5	3	4	9,234.8	710.0	169.3	30.0	60.0	10,204.1
0.5	0.5	5	6,994.1	1,500.0	507.8	10.0	26.0	9,038.0
1	0.5	5	7,183.5	1,500.0	253.9	10.0	26.0	8,973.4
1.5	0.5	5	7,355.1	1,500.0	169.3	10.0	26.0	9,060.4
0.5	1	5	7,240.3	1,324.0	507.8	10.0	26.0	9,108.1
1	1	5	7,411.8	1,324.0	253.9	10.0	26.0	9,025.7
1.5	1	5	7,591.2	1,324.0	169.3	10.0	26.0	9,120.5
0.5	2	5	7,787.6	920.0	507.8	10.0	26.0	9,251.4
1	2	5	7,963.9	920.0	253.9	10.0	26.0	9,173.8
1.5	2	5	8,147.2	920.0	169.3	10.0	26.0	9,272.4
0.5	3	5	8,427.7	698.0	507.8	10.0	26.0	9,669.5
1	3	5	8,607.6	698.0	253.9	10.0	26.0	9,595.5
1.5	3	5	8,799.0	698.0	169.3	10.0	26.0	9,702.3
0.5	0.5	6	7,046.7	1,395.0	507.8	0.0	0.0	8,949.5
1	0.5	6	7,213.4	1,395.0	253.9	0.0	0.0	8,862.3
1.5	0.5	6	7,371.4	1,395.0	169.3	0.0	0.0	8,935.7
0.5	1	6	7,254.8	1,153.0	507.8	0.0	0.0	8,915.7
1	1	6	7,414.8	1,153.0	253.9	0.0	0.0	8,821.7
1.5	1	6	7,576.0	1,153.0	169.3	0.0	0.0	8,898.3
0.5	2	6	7,738.4	749.0	507.8	0.0	0.0	8,995.2
1	2	6	7,907.0	749.0	253.9	0.0	0.0	8,909.9
1.5	2	6	8,071.2	749.0	169.3	0.0	0.0	8,989.5
0.5	3	6	8,318.0	662.0	507.8	0.0	0.0	9,487.9
1	3	6	8,483.2	662.0	253.9	0.0	0.0	9,399.1
1.5	3	6	8,654.6	662.0	169.3	0.0	0.0	9,485.9

B.4 San Jose

Parameters (°C)			Present Value ($K)					
HX Approach	CT Approach	Range	15-Year Electrical and Water	CT	HX	Pumps	Pipe & fittings	Total
0.5	0.5	3	10,452.0	1,742.0	507.8	50.0	111.0	12,862.8
1	0.5	3	11,057.7	1,742.0	253.9	50.0	111.0	13,214.6
1.5	0.5	3	11,724.5	1,742.0	169.3	50.0	111.0	13,796.7
0.5	1	3	11,460.1	1,434.0	507.8	50.0	111.0	13,562.9
1	1	3	12,167.5	1,434.0	253.9	50.0	111.0	14,016.4
1.5	1	3	13,101.4	1,434.0	169.3	50.0	111.0	14,865.7
0.5	2	3	14,150.2	970.0	507.8	50.0	111.0	15,789.0
1	2	3	15,057.3	970.0	253.9	50.0	111.0	16,442.2
1.5	2	3	15,912.5	970.0	169.3	50.0	111.0	17,212.8
0.5	3	3	16,991.6	785.0	507.8	50.0	111.0	18,445.5
1	3	3	17,747.7	785.0	253.9	50.0	111.0	18,947.6
1.5	3	3	18,406.1	785.0	169.3	50.0	111.0	19,521.4
0.5	0.5	4	9,727.4	1,550.0	507.8	30.0	60.0	11,875.2
1	0.5	4	10,223.3	1,550.0	253.9	30.0	60.0	12,117.2
1.5	0.5	4	10,772.5	1,550.0	169.3	30.0	60.0	12,581.7
0.5	1	4	10,510.6	1,267.0	507.8	30.0	60.0	12,375.4
1	1	4	11,078.1	1,267.0	253.9	30.0	60.0	12,689.0
1.5	1	4	11,855.9	1,267.0	169.3	30.0	60.0	13,382.1
0.5	2	4	12,635.0	930.0	507.8	30.0	60.0	14,162.8
1	2	4	13,430.7	930.0	253.9	30.0	60.0	14,704.6
1.5	2	4	14,188.7	930.0	169.3	30.0	60.0	15,377.9
0.5	3	4	15,124.0	715.0	507.8	30.0	60.0	16,436.8
1	3	4	15,748.4	715.0	253.9	30.0	60.0	16,807.3
1.5	3	4	16,393.9	715.0	169.3	30.0	60.0	17,368.2
0.5	0.5	5	9,638.0	1,400.0	507.8	10.0	26.0	11,581.8
1	0.5	5	10,077.7	1,400.0	253.9	10.0	26.0	11,767.6
1.5	0.5	5	10,560.4	1,400.0	169.3	10.0	26.0	12,165.6
0.5	1	5	10,328.2	1,039.0	507.8	10.0	26.0	11,911.0
1	1	5	10,825.3	1,039.0	253.9	10.0	26.0	12,154.2
1.5	1	5	11,486.6	1,039.0	169.3	10.0	26.0	12,730.8
0.5	2	5	12,187.7	819.0	507.8	10.0	26.0	13,550.5
1	2	5	12,860.8	819.0	253.9	10.0	26.0	13,969.7
1.5	2	5	13,493.7	819.0	169.3	10.0	26.0	14,518.0
0.5	3	5	14,398.7	679.0	507.8	10.0	26.0	15,621.5
1	3	5	14,887.4	679.0	253.9	10.0	26.0	15,856.4
1.5	3	5	15,437.0	679.0	169.3	10.0	26.0	16,321.3
0.5	0.5	6	9,690.0	1,300.0	507.8	0.0	0.0	11,497.8
1	0.5	6	10,118.4	1,300.0	253.9	0.0	0.0	11,672.3
1.5	0.5	6	10,585.1	1,300.0	169.3	0.0	0.0	12,054.4
0.5	1	6	10,357.7	963.0	507.8	0.0	0.0	11,828.5
1	1	6	10,867.4	963.0	253.9	0.0	0.0	12,084.3
1.5	1	6	11,479.3	963.0	169.3	0.0	0.0	12,611.6
0.5	2	6	12,134.8	663.0	507.8	0.0	0.0	13,305.6
1	2	6	12,757.6	663.0	253.9	0.0	0.0	13,674.5
1.5	2	6	13,333.2	663.0	169.3	0.0	0.0	14,165.4
0.5	3	6	14,173.1	524.0	507.8	0.0	0.0	15,204.9
1	3	6	14,650.5	524.0	253.9	0.0	0.0	15,428.4
1.5	3	6	15,123.6	524.0	169.3	0.0	0.0	15,816.8

B.5 Washington DC

Parameters (^{o}C)			Present Value ($K)					
HX Approach	CT Approach	Range	15-Year Electrical and Water	CT	HX	Pumps	Pipe & fittings	Total
0.5	0.5	3	11,404.2	1,124.0	507.8	50.0	111.0	13,197.0
1	0.5	3	11,592.3	1,124.0	253.9	50.0	111.0	13,131.3
1.5	0.5	3	11,771.4	1,124.0	169.3	50.0	111.0	13,225.6
0.5	1	3	11,916.3	1,023.0	507.8	50.0	111.0	13,608.1
1	1	3	12,089.9	1,023.0	253.9	50.0	111.0	13,527.8
1.5	1	3	12,285.2	1,023.0	169.3	50.0	111.0	13,638.5
0.5	2	3	13,024.3	739.0	507.8	50.0	111.0	14,432.1
1	2	3	13,227.0	739.0	253.9	50.0	111.0	14,380.9
1.5	2	3	13,444.2	739.0	169.3	50.0	111.0	14,513.5
0.5	3	3	14,257.2	630.0	507.8	50.0	111.0	15,556.0
1	3	3	14,504.9	630.0	253.9	50.0	111.0	15,549.8
1.5	3	3	14,713.1	630.0	169.3	50.0	111.0	15,673.4
0.5	0.5	4	10,654.8	1,257.0	507.8	30.0	60.0	12,509.7
1	0.5	4	10,808.3	1,257.0	253.9	30.0	60.0	12,409.2
1.5	0.5	4	10,955.3	1,257.0	169.3	30.0	60.0	12,471.6
0.5	1	4	11,089.9	953.0	507.8	30.0	60.0	12,640.8
1	1	4	11,229.9	953.0	253.9	30.0	60.0	12,526.8
1.5	1	4	11,388.9	953.0	169.3	30.0	60.0	12,601.1
0.5	2	4	12,001.2	672.0	507.8	30.0	60.0	13,271.0
1	2	4	12,169.8	672.0	253.9	30.0	60.0	13,185.7
1.5	2	4	12,350.6	672.0	169.3	30.0	60.0	13,281.9
0.5	3	4	13,013.4	515.0	507.8	30.0	60.0	14,126.3
1	3	4	13,219.6	515.0	253.9	30.0	60.0	14,078.5
1.5	3	4	13,415.5	515.0	169.3	30.0	60.0	14,189.7
0.5	0.5	5	10,396.8	1,157.0	507.8	10.0	26.0	12,097.7
1	0.5	5	10,515.2	1,157.0	253.9	10.0	26.0	11,962.1
1.5	0.5	5	10,632.5	1,157.0	169.3	10.0	26.0	11,994.8
0.5	1	5	10,780.4	888.0	507.8	10.0	26.0	12,212.2
1	1	5	10,892.0	888.0	253.9	10.0	26.0	12,069.9
1.5	1	5	11,030.2	888.0	169.3	10.0	26.0	12,123.4
0.5	2	5	11,572.9	614.0	507.8	10.0	26.0	12,730.8
1	2	5	11,709.6	614.0	253.9	10.0	26.0	12,613.6
1.5	2	5	11,866.6	614.0	169.3	10.0	26.0	12,685.9
0.5	3	5	12,440.0	560.0	507.8	10.0	26.0	13,543.8
1	3	5	12,611.5	560.0	253.9	10.0	26.0	13,461.4
1.5	3	5	12,783.3	560.0	169.3	10.0	26.0	13,548.6
0.5	0.5	6	10,283.9	1,146.0	507.8	0.0	0.0	11,937.7
1	0.5	6	10,390.8	1,146.0	253.9	0.0	0.0	11,790.7
1.5	0.5	6	10,491.9	1,146.0	169.3	0.0	0.0	11,807.2
0.5	1	6	10,647.5	729.0	507.8	0.0	0.0	11,884.4
1	1	6	10,751.8	729.0	253.9	0.0	0.0	11,734.7
1.5	1	6	10,873.0	729.0	169.3	0.0	0.0	11,771.2
0.5	2	6	11,392.5	607.0	507.8	0.0	0.0	12,507.3
1	2	6	11,520.1	607.0	253.9	0.0	0.0	12,381.1
1.5	2	6	11,652.0	607.0	169.3	0.0	0.0	12,428.3
0.5	3	6	12,207.4	459.0	507.8	0.0	0.0	13,174.2
1	3	6	12,353.0	459.0	253.9	0.0	0.0	13,065.9
1.5	3	6	12,488.9	459.0	169.3	0.0	0.0	13,117.2