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Optimizing Ice Thermal Storage To Reduce Energy Cost

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Optimizing Ice Thermal Storage to Reduce Energy Cost

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Biographical Sketch

Christopher L. Hall was born on March 24, 1990 in Greenville, North Carolina. He is a second year graduate student from Ahoskie, North Carolina. Presently, he is pursuing a Master of Science degree in Civil Engineering from The North Carolina Agricultural and Technical State University. In May of 2012 Christopher earned the Bachelor of Science degree in Architectural Engineering, also at NC A&T State University.

While studying architectural engineering throughout his undergraduate career, he was awarded for his academic success and high standard for achievement. During undergrad he was recognized and inducted into the Tau Beta Pi honor society, exclusively for top tier engineering students, as well as Phi Alpha Epsilon, an honor society for high level architectural engineering students. He was a well-rounded architectural engineering student as he found interest in the design, lighting and electrical disciplines.

It was at the end of his undergraduate tenure that he decided to further his studies in pursuit of a graduate degree focused on Building Energy. This focus in graduate school allowed him to work with his major professor and eventually conduct research. After a year of graduate school Christopher was able to land a summer internship which fell directly in line with his studies and provided clarity to his thesis research. He spent the summer of 2013 in Champaign, Illinois and worked as a research intern for the U.S. Army Corps of Engineers.

Dedication

I would like to dedicate this thesis to anyone who finds a way when things may seem impossible. My greatest characteristic is my persistence. Smart people are a dime a dozen. What matters is the ability to think different… to think out of the box.

Acknowledgements

I would like to acknowledge the U.S. Army Corps of Engineers and their Engineer Research and Development Center/Construction Engineering Research Laboratory. Spending a summer working with them and having the privilege and opportunity to work in the same field as my thesis research proved to be highly beneficial in my research efforts. The mentoring and guidance provided was superior and greatly appreciated. I would like to give special thanks to Dr. Nathaniel Putnam, who was my direct mentor with the Environmental Processes Branch. He helped me to design and develop a project that would allow me to grow as a research student, attain vital information contributing to my thesis research, all while providing a useful and valuable reference point for the study to help the branch office where he works.

Most importantly, I have to thank my advisor at NC A&T State University, Dr. Nabil Nassif. He took me in as one of his Master Thesis students with no hesitation, although he still advises a number of other MS and PhD students. This research and thesis was a huge success due to his efforts. His experience and knowledge in HVAC and the field of energy alone is unbelievable. While working with him I noticed how valuable his guidance and opinion meant to my research work as well as my advancement towards succeeding and graduating. Time after time Dr. Nassif never failed in constantly pushing me to do more and aim higher. He aided me in many ways and made sure I had the tools to become successful and grow as an individual in my early career. It was truly a pleasure working directly with him for the last couple of years. I thank you Dr. Nassif for truly caring about me and my work and seeing to it that I graduated a better student and a promising career individual.

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Abstract

Energy cost for buildings is an issue of concern for owners across the U.S. The bigger the building, the greater the concern. A part of this is due to the energy required to cool the building and the way in which charges are set when paying for energy consumed during different times of the day. This study will prove that designing ice thermal storage properly will minimize energy cost in buildings. The effectiveness of ice thermal storage as a means to reduce energy costs lies within transferring the time of most energy consumption from on-peak to off-peak periods. Multiple variables go into the equation of finding the optimal use of ice thermal storage and they are all judged with the final objective of minimizing monthly energy costs. This research discusses the optimal design of ice thermal storage and its impact on energy consumption, energy demand, and the total energy cost. A tool for optimal design of ice thermal storage is developed, considering variables such as chiller and ice storage sizes and charging and discharge times. The simulations take place in a four-story building and investigate the potential of Ice Thermal Storage as a resource in reducing and minimizing energy cost for cooling. The simulations test the effectiveness of Ice Thermal Storage implemented into the four-story building in ten locations across the United States.

CHAPTER 1

Introduction

1.1 Thesis Format and Flow

This thesis consists of five chapters, organized to separate the major points in the progression of the research. The first chapter is a preliminary chapter and serves to introduce the topic while providing any necessary background information. Following this, chapter two is the chapter for literature review, where the bulk of the research's resources reside. Here in the second chapter a number of references are made to support the research with direct quotations for the most important information. The third chapter is all about the simulations and research. Throughout this chapter the models will be explained followed by a detailed building description and a methodology behind the experiment. In the fourth chapter is where the results will be located. In this chapter a number of tested results will be revealed and compared to other findings. The fifth chapter is the last major section and will be the home for the discussion and conclusion of the entire research, a deeper analysis of results, and at the very end a suggestion into where the research should go moving forward. After the major chapters is where the references can be found, listed alphabetically, followed by the appendices of all research work not directly listed in the body of the thesis.

1.2 Key Terms and Definitions

A. eQuest: a building energy software tool developed by the U.S. Department of Energy. It is a widely used, time-proven whole building energy performance design tool. It has wizards, interactive graphics, parametric analysis, and rapid execution. This makes eQuest able to conduct whole-building performance simulation analysis throughout the entire design process, from the design stage with a schematic design wizard all the way up to a very detailed design development stage.

B. Dry Bulb Temperature: the temperature of air measured by a thermometer freely exposed to air, yet shielded from radiation and moisture. Dry bulb temperature is the temperature that is usually thought of as air temperature, and the true thermodynamic temperature. This temperature is typically expressed in degrees Celsius, Kelvin, and/or Fahrenheit.

C. Wet Bulb Temperature: the temperature a parcel of air would have if it were cooled to saturation by the evaporation of water into it, with latent heat supplied by the parcel. Wet bulb temperature is the temperature felt when the skin is wet and exposed to moving air.

D. MatLab: a numerical computing environment and fourth generation programming language. It allows for matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages like: C, C++, Java, and Fortran.

E. Chiller: A device that removes heat from a liquid by a vapor-compression or absorption refrigeration cycle. This cooled liquid flows through pipes in a building and passes through coils in air handlers, fan-coil units, or other systems, cooling and usually dehumidifying the air in the building.

F. Air Handling Unit: (AHU) A central unit consisting of a blower, heating and cooling elements, filter racks or chamber, dampers, humidifier, and other central equipment in direct contact with the airflow.

G. ASHRAE: (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) is an organization devoted to the improvement of indoor-environment-control technology in the heating, ventilation, and air conditioning industry.

H. ASHRAE Climate Zones: a sorted distribution of regions in the United States based on climate characteristics split into 7 zones.

1.3 Introduction

There is a cause for concern with the related energy cost that goes hand in hand with big commercial buildings. Efforts are now widespread in making buildings as energy efficient as possible. It is not always necessary to gain energy efficiency through expensive investments in large equipment and technological improvements. Inexpensive efforts to gain energy efficiency can come from a number of techniques whether it is something as simple as minor maintenance, how the building is operated, or even the behavior of building tenants. The other more expensive building enhancements can range from upgrades to energy-efficient lighting, air sealing, and HVAC equipment, just to name a few. Another form of improving a building's energy cost can be provided by storing excess thermal energy for usage at a later time. This technology is known as Thermal Energy Storage (TES) and has numerous methods in which energy can be stored and kept for use in the future.

1.4 Purpose of Exploratory Research

1.4.1 Energy use in commercial and industrial buildings. There are over five million combined commercial and industrial buildings in the United States. The annual energy costs for these buildings exceed two hundred billion dollars (Energy Efficiency and Renewable Energy, 2010). In addition, it is estimated that about thirty percent of the energy in the commercial and industrial buildings are deemed to be used inefficiently or unnecessarily. If the energy efficiency in commercial and industrial buildings in the United States could be enhanced by ten percent at the very least, the amount of money it would save annually would tip the scales at twenty billion dollars. These facts show just how important it is to make a change in the operation of commercial and industrial buildings towards a more efficient state. One way to move in that direction is to add and incorporate some sustainable practices and technology. A possibility that will be investigated is whether the incorporation of ice thermal storage can provide enough of a savings in commercial and industrial buildings, no matter if it is in a dominantly hot or cold climate.

1.4.2 Ice thermal storage as a sustainable technology. It has been shown that ice thermal storage can save on a building's energy cost. It would be a great improvement to HVAC equipment adding ice thermal storage for savings in commercial and industrial buildings. It is important to note however, that in order to gain the savings to make ice thermal storage worth it the system must be optimized to achieve maximum benefits. The purpose of this study is to test the implementation of ice thermal storage and to estimate just how much savings in energy cost that can be obtained. In addition to those savings the study will investigate the differences in the use of this technology in numerous locations throughout the United States, in order to compare savings possibilities with respect to weather and climate. This study looks to explore and ultimately confirm if in fact ice thermal storage can prove beneficial in a colder climate from a strictly energy cost saving standpoint. The use of ice thermal storage in a dry and generally hotter climate is expected to show more of a savings than it would be expected to produce in a wetter, colder climate. This will give an additional option to add to energy cost savings measures. The basis of this research will be able to be used in any location with some minor changes to input variables and provide output for the use of ice thermal storage as proving to be beneficial and cost-effective or not.

1.5 Thermal Energy Storage (TES)

The central idea behind thermal energy storage lies within harnessing energy and saving it for later use. Thermal energy storage is available in a wide range of fields that span; solar energy, heat storage (in rocks, tanks, concrete, and electric heaters), cryogenic energy, or even molten salt technology. Although there are multiple different systems in which thermal energy can be stored, it is most common that it is used to provide a cooling capacity within commercial buildings. Thermal energy storage through cooling allows for huge money savings and can increase the efficiency of a building's current HVAC equipment. This form of thermal energy storage is referred to as Ice Thermal Storage.

1.6 Ice Thermal Storage (ITS)

1.6.1 Introduction to ice thermal storage. Ice thermal storage has shown to be a very capable technology in reducing energy cost, particularly in bigger commercial buildings. The main objective behind ice thermal storage technology which provides the ability to reduce energy cost comes from the shifting of energy consumption loads during the highly expensive on-peak periods of the day to a more affordable off-peak period. The savings behind this technology is evident but there lies no financial gain from the use of ice thermal storage when the system is designed and runs poorly in combination with the building's HVAC equipment.

1.6.2 The variables behind ice thermal storage. With the savings that can result from the use of ice thermal storage comes a lot of inner conditions that require tuning. These inner conditions adjusted and set correctly is what provides the biggest savings in ice thermal storage and a building's energy costs. Such variables include: location weather data and utility rate structure, ice capacity factor, ice charge time, ice discharge time, and a chiller size factor. Some of these variables have wide ranges of possibilities and others are standards that can be decided upon. All in all, the location is a big determination in how many of the other conditions are resolved. Each condition requires some attention and insight but any and every adjustment can have some effect on final outcomes of energy cost, as well as energy consumption.

1.6.3 Ice thermal storage: how it works. As previously stated, the savings of ice thermal storage technology results from the shifting of the daytime cooling load that is considered on-peak time to the off-peak periods where the cost of energy is substantially much cheaper. Generally this is done so by setting the building's HVAC equipment to run in the evening and/or throughout the night. During this time the HVAC system is running and makes ice that is stored in the ice thermal storage tanks. This ice that is made during the evening and night is stored and kept in order to cool the building the following day during the on-peak period of the day. By running the equipment in this way the chiller never turns on during the on-peak period of the day, therefore, no extra energy charges incur. The chiller runs during the night preparing the ITS tanks for cooling during the on-peak period, once the building becomes operational in the morning, the charging of the ITS tanks ceases and the chiller returns to normal operation. In the morning the chiller runs cooling the building as it normally would. It is when the on-peak period of the day starts that the chiller shuts off and the ITS tanks with the charged ice cools the building in place of the chiller. This cooling by the ITS tanks takes places until the ice runs out and if needed the chiller will turn back on. If designed appropriately, the ice thermal storage tanks would have enough capacity of ice to cover the entire on-peak period of day and cool the building until it becomes closed. This cycle of charging ice and discharging the ice during on-peak costs would continue daily to provide cooling when the building is operational for as long as cooling is needed, depending on the weather and season.

1.6.4 Downside to ice thermal storage. The benefits that ice thermal storage technology provides are very much apparent. It is not as evident however of the small hindrance that ice thermal storage also causes. Although the implementation of ITS results in a savings on energy cost for buildings, ice thermal storage ultimately increases the amount of energy consumption that is caused by the building. This increase in energy consumption however is only a minor concern because of the savings that is due to the decline in energy costs. The increase in the amount of energy consumed by the building with the addition of ice thermal energy is most easily explained and accounted for by the operation of the chiller. With the employment of ITS the chiller runs at night. When the chiller has to run at night to make the ice for the ITS tanks it is required to run at a higher capacity to be cold enough, making ice. The energy consumption increase is due to the extent of how much harder the chiller works and runs while making ice. The positive in this outcome lies in the fact that the savings in energy cost fortunately outweighs the amount in which the energy consumption increases, and it does so substantially**.**

1.7 Research Constraints

Some of the major constraints within this research include: the utility rate structure, and the building study. The constraints in this study are minor and the research has been adapted to the point where adjustments can be made for future use and alternative research moving forward. This study makes it so the results shown are adequate for the building used and in the location set forth.

1.7.1 Utility rate structure. Throughout the study, one constraint lies around the utility rate structure. For research purposes one utility rate structure was used in all locations. This means results show how the weather affects usage of ITS in various locations and how it changes the optimization of the system. It is however possible to manually adjust the utility rate structure for a location in future works, if provided. In order to find the true optimal results for a particular location, a utility rate structure for an electric company in the local area would be required.

1.7.2 Building study. Another constraint involves the building study. This research was done with an office building that was the same for each location, where only the location and weather information was changed. This was done for purposes of comparisons between the test locations. Future studies would require the specific building being investigated to be entered into eQuest. This will allow for the building loads to be calculated and sizing of all HVAC equipment will result from this; including variables that go into sizing the ITS system. Ultimately loading a floor plan and specific information for the exact building will permit true results for savings of that building if it were incorporated with ice thermal storage.

1.8 Objectives

The overall objective of this study is very much apparent as it all boils down to the pursuit of savings on energy costs. There are however, other objectives that contribute to the success of the overall objective and play an important role in the development of this research. One specific objective is to develop an optimization design tool for ice thermal storage. This optimization design tool also includes a simulation model for simulating results and testing input design variables. The simulation model was developed using MatLab code. The cooling load used within the simulation model is attained using the simulation software known as eQUEST. The final part of the optimization design tool is the major piece that solves the optimization for the design variables. MatLab provides an optimization genetic algorithm tool within its program as an add-on and this is used for the optimization design process.

CHAPTER 2

Literature Review

2.1 Overview

The literature reviewed prior to this research was vital in gaining and understanding necessary background knowledge before moving forward. Numerous articles were explored from countless sources. This stage of research was based on targeting and setting a great foundation and structure of preceding knowledge of works on ice thermal storage technology, as well as other important categories such as optimization principles, among other subjects and topics of discussion. Reading some of the writings found about this topic served as an abundant resource which allowed for strong inferences and conclusions to be made about the programming model. In total, the review of literature made it possible for the data tested to be understood and interpreted rather easily than initially imagined.

2.2 Energetic, Economic, and Environmental Benefits of Utilizing the Ice Thermal Storage Systems for Office Building Applications

This article was written by researchers in Malaysia concerning the effectiveness of ice thermal storage and the feasibility of employing such practices successfully. The study was designed and focused to target the active, financial, as well as the ecofriendly profits of implementing ice thermal storage technologies for office building cooling applications. Air conditioning (AC) systems account for between 16 and 50% of electricity consumption in many regions around the world, especially in hot and humid countries near the Equator the electricity consumption might be more (Rismanchi, 2012). People spend around 90% of their time in buildings while about 40% of primary energy needs are due to buildings (Rismanchi, 2011). Here lies more confirmation, from a statistical standpoint, of the weight buildings are guilty of carrying in energy consumption. It is for a fact known that cooling of buildings are a big portion of this energy consuming problem within buildings. Efforts to reduce or make a positive impact on the struggles cooling poses in energy needs due to buildings have well been documented. The ability for ice thermal storage systems to account for such positive results has well been explored and experimented. The gradual development of cold thermal energy storage (CTES) technology over the past decade has allowed for wide deployment in many countries, and it is now considered as one of the best energy saving approaches for AC systems (Rismanchi, 2012). These thermal energy storage systems have been most commonly used in buildings commercially such as office buildings, hospitals, schools, and even churches. The implementation of a thermal storage system simply means adding on to the already current AC system in place for the cooling of the building. Instead of cooling being done by the chiller during on-peak hours of the day, a new variable known as the thermal storage system is introduced and charged during off-peak time. During the on-peak periods of the day when cooling is needed, the thermal storage system then kicks in and provides cooling for the building, allowing for the chiller to shut off and not incur on-peak charges. Differences between a typical AC system and a system designed with thermal energy storage can been seen below in Figure 1. This system implemented into building applications can result in big savings of energy costs. The statistical data show that office buildings consume around 21% of the total electricity consumption of the country (Rismanchi, 2012). These types of alarming facts combined with the potential shown to be evident in thermal storage technologies provide a great deal of potential in advancing the systems discussed and improving upon energy costs concerns. All in all, this article was presented to examine the economic and environmental benefits of using ice thermal storage systems in commercial buildings.

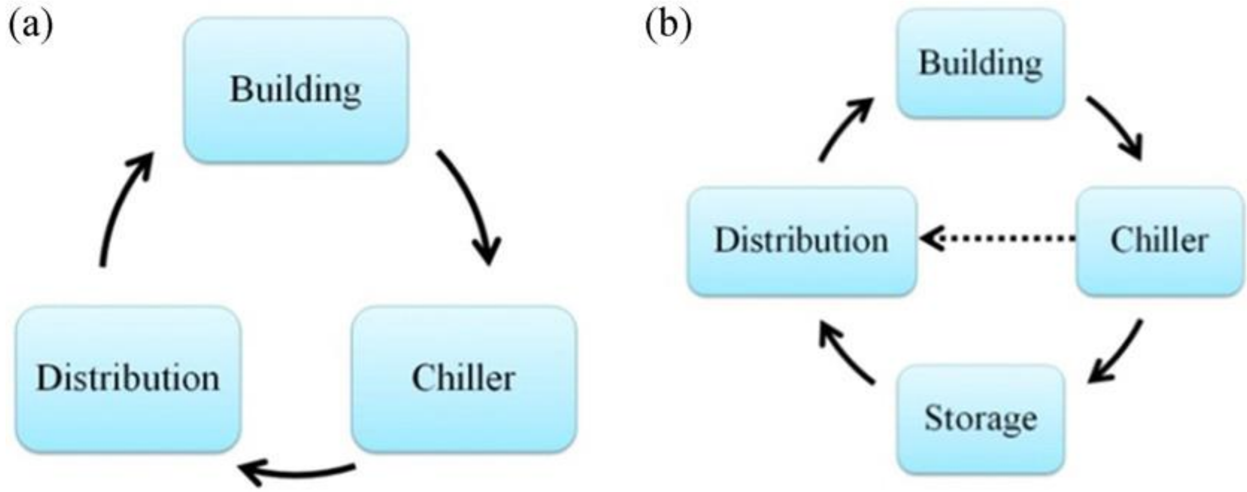

Figure 1 Schematic of (a) conventional AC system & (b) TES system (Rismanchi,2012)

2.3 Optimal Control of Building Storage Systems Using Both Ice Storage and Thermal Mass - Part I: Simulation Environment

Two possibilities for storing thermal energy are presented in this article and are discussed based on a simulation environment. Researchers in this study have created a simulation environment that can test the productiveness of both, ice storage as well as thermal mass, in reducing operating costs.

> There are two common approaches to store cooling thermal energy in buildings: active and passive systems. The active systems consist of ice or chilled water storage tanks, commonly known as thermal energy storage (TES) systems, which are charged at night and discharged during the day. The passive systems utilize the thermal mass of the building materials to pre-cool the building at night when the electrical rates are low. Both active and passive systems have been used to shift some of the cooling loads from on-peak to off-peak utility rate periods (Hajiah, 2012 a).

The research experiment for this article sets up an environment where both the aggressive and passive system is tested. In this experiment there is an environment simulation that assesses numerous control strategies possessed by thermal energy storage technologies. A flowchart can be seen in Figure 2 of how the simulation environment operates. Major sections of the simulation environment consist of: Input Data, Building Models, Control Strategies, and Controlled Building. The input is information ready in by the user and serves as certain parameters that must be abided by throughout the process. This ranges from the make-up of the building to such things as utility rate structure and weather data. The building models module is where estimates and simulations of thermal loads take place, including the measured energy demands that will be needed for cooling. As the flow continues into the control strategies stage, this is when the determining optimal control strategies took place. From there those parameters move into the controlled building. This last flow module is used in assessing the optimal control strategies performance. The last two major sections continue to circulate, solving and re-analyzing the optimal control strategies until the most optimal solution is determined. From this research, the findings by the simulation environment were validated by measured data using a full-scale laboratory test. Since the simulation environment is model based, it can be applied to a wide range of building types and operating conditions (Hajiah, 2012 a). This article was written to display the findings from research involving the testing of both thermal mass and an ice storage system to reduce total operating costs in addition to retaining thermal comfort for the building occupants within commercial buildings. This was done so using a simulation environment which was then later authenticated in a full-scale research lab. The results of the validation analysis indicated that the simulation environment predict cost savings for optimal controls with 10% agreement when compared to the experimental measurements (Hajiah, 2012 a).

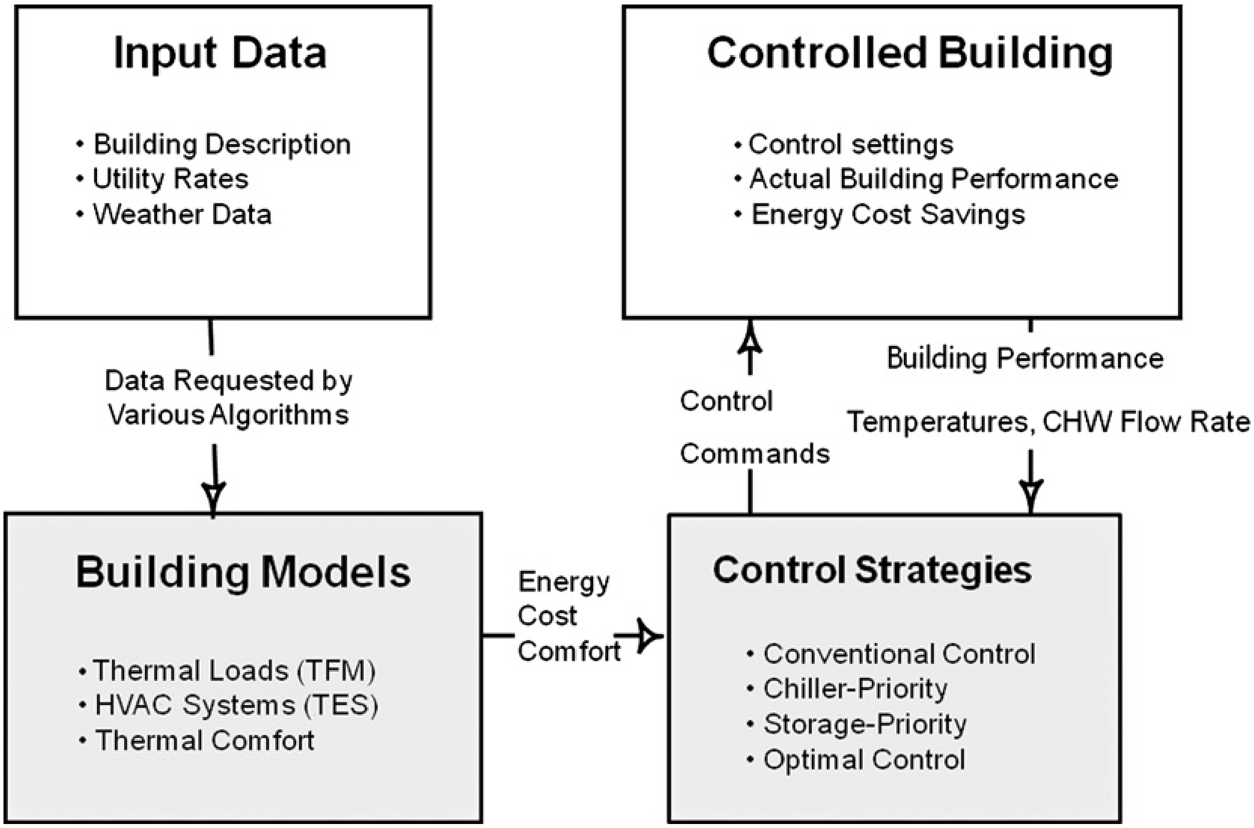

Figure 2 Flowchart of the simulation environment (Hajiah, 2012 a).

2.4 Optimal Controls of Building Storage Systems Using Both Ice Storage and Thermal Mass - Part II: Parametric Analysis

This article is basically a sequel or companion paper to the previous article discussed in the last section. The prequel to this article consisted of a simulation environment that tested benefits of thermal capacitance and ice storage systems to reduce energy costs. In the sequel, this article presents different parametric analysis to examine influences that affect the efficiency of thermal energy usage in reducing total energy costs. The most general and straightforward strategy of thermal energy storage entails charging the ice storage while operating the chiller during low electric charge periods, known as off-peak time. When the expensive on-peak time occurs the ice storage is then discharged and meets the building required cooling load. As a result, it is possible to reduce or even eliminate the chiller operation during on-peak hours (Hajiah, 2012 b). The parametric study that took place in this article paper was based upon the simulation environment from the preceding paper. The analysis by this research included multiple parameters such as; the optimization cost function, base chiller size, and ice storage tank capacity, as well as weather conditions. The focus here will be on the simulation model analysis; including parameters like the building model, utility rate structure, and optimization cost function. The building for the study was a simple rectangular office building consisting of five zones, nine foot wall heights, operational times from 8:00am to 5:00pm, and typical standard lighting fixtures, appliances, and miscellaneous equipment. The research's utility rate structure had an on-peak time set from 10:00am to 10:00pm, and an on-peak energy charge of $0.0208/kWh, with a $7.50/kW for demand charges. The off-peak charges were set at zero, and this consisted of anytime that wasn't considered to on-peak time. For the optimization cost function, the simulation environment was used from the prior article in setting up the parametric analyses. The optimization strategies are evaluated against the following base controls:

1. Conventional control of cooling system using a fixed temperature set point of 76 degrees Fahrenheit from 8:00 am to 5:00 pm. This base case is selected to investigate the effectiveness of using building thermal mass.

2. Chiller-priority control when an ice storage system is utilized (Hajiah, 2012 b).

There were a number of parametric analyses that were done using the office building model in determining the efficiency of thermal mass and ice storage under various conditions. The research from this study took place as if the building was located in Chicago, Illinois, meaning that the climate and weather data from this city was taken into account during testing. In end, the second version of this two-part series of articles has examined many of the important factors that affect the performance of the optimal controls using thermal mass and ice storage to reduce the cooling system's total operating costs. The optimization results discussed in this paper for a typical office building model under different weather conditions and various design options indicate that significant cost savings (up to 40%) can be achieved in the cooling system total operating cost. Generally, the results indicate that optimal control for both building thermal mass pre-cooling and ice storage operation outperforms all of other conventional controls and sequential optimal controls under all climate conditions, utility rate structures, and system designs (Hajiah, 2012 b).

2.5 Cumulative Energy Analysis of Ice Thermal Storage Air Conditioning System

This article is out of the Applied Energy journal and focuses on the cumulative energy analysis method. The research analyzes the effects of implementing an ice thermal storage air conditioning system into a building power supply. The work completed in this article is a product of researchers out of China. Along with the fast-paced development of modern construction in China, the energy consumption of air conditioning increases rapidly and is fast approaching the international level. As the environmental temperature changes, the cooling load and the electricity consumption change correspondingly (Pu, 2012). This meant that as the outside temperatures rose, so did the building's required cooling load, as well as the energy consumption. In opposition to most studies, the research found in this article examines the effects of ice thermal storage based upon resource utilization. This is known as using the approach of cumulative energy analysis. It is defined so that the cumulative energy consumption of a product is the total energy of all the consumed natural resources (Pu, 2012). Studies have shown that cumulative energy analysis is a valuable analysis method based on the concept of resource consumption. However, there is no study that can take claim for investigation of ice thermal storage air conditioning systems from a standpoint of cumulative energy consumption. This article provides models for the cumulative energy analysis for ice thermal air conditioning systems with all stages consuming any energy provided by the peak regulating unit considered. Results are provided and validated by two case studies. It was found to be a linear relationship between the average cumulative energy variation and both the operating load of the power unit as well as the load of ice thermal storage. It shows that the cumulative energy variation decreases as either of the other two increases.

2.6 Performance of Ice Storage System Utilizing a Combined Partial and Full Storage Strategy

This journal article is research from three individuals out of a University in Iraq that looks for vital information in expanding the current knowledge of ice thermal storage technology and its efficiency depending upon the type of storage strategy. This is the first work that is discussed where more than one charge strategy is addressed or compared and contrasted. In this research ice storage strategies that are discussed include: a combined system, a partial storage system, and a full load storage system. Thermal storage is the temporary storage of high or low temperature energy for later use (Al-Qalamchi, 2007). With the different storage strategies, experiments were done to decide the potential savings in chiller size in comparison to that of a more conventional cooling system. The main outcome of this research was to optimize the chiller size for the combined ice charge strategy, known for utilizing both the partial and full storage systems. Results turned out that the combined ice strategy system needed a much larger equipment size in order to meet the cooling load. Combined strategy required chiller size was found to decrease with decrease in on-peak period, hence the optimum chiller size for this new strategy was found to occur at zero on-peak hours, and i.e., when the combined system starts to operate as a partial strategy system (Al-Qalamchi, 2007). The key conclusions drawn from the research of this article are vital in understanding the different ice charge strategies, including which ones to move forward with in researching deeper. Some other key takeaways included:

1) Combined strategy system requires less chiller size than conventional system does. A reduction of about 28% may be achieved.

2) Partial chiller strategy requires less chiller size than combined system.

3) Combined strategy chiller size was found to decrease with decrease in on-peak period (Al-Qalamchi, 2007).

2.7 Optimal Design and Control of Ice Thermal Storage System for a Typical Chilled Water Plant

This article focuses around the optimal design of an ice thermal storage system for a typical chilled water plant. The research takes a case study for a real office building located in Florida. Thermal energy storage includes a number of technologies that store thermal energy in energy storage tanks for later use. These applications include the production of ice or chilled water at night which is then used to cool the building during the day. Unfortunately, thermal storage may not provide the expected load shifting or the cost saving if not designed or operated properly. This research discusses the optimal design of ice thermal storage and its impact on energy consumption, demand, and total energy cost. The emphasis on the use of ice thermal storage as an effort to reduce energy costs lies within transferring the time of most energy consumption from on-peak to off-peak periods. Multiple variables go into the equation of finding the optimal use of ice thermal storage and they are all judged with the final objective of minimizing monthly energy costs. This research discusses the optimal design of ice thermal storage and its impact on energy consumption, demand, and total energy cost. A tool for optimal design of ice storage is developed, considering variables such as chiller and ice storage sizes along with ice charge and discharge times. Detailed simulation studies using a real office building located near Orlando, FL including the utility rate structure are presented. The study considers the effect of the ice thermal storage on the chiller performance and the associated energy cost and demonstrates the cost saving achieved from optimal ice storage design. A whole building energy simulation model is used to generate the hourly cooling load for both the design day and the entire year. Other collected variables such as condenser entering water temperature, chilled water leaving temperature, outdoor air dry bulb and wet bulb temperatures are used as inputs to a chiller model based on DOE-2 chiller model to determine the associated cooling energy use (Nassif, 2014 b). The results show a significant energy costs savings can be attained when optimized ice storage design is utilized by the tool proposed in this article.

> The results demonstrated that although the energy consumption increases by using ice thermal storage, the energy cost drops significantly, mainly depending on the local utility rate structure. It showed a significant cost energy saving can be obtained by optimal ice storage design through using the tool that proposed in this paper. The saving could be up to 28% comparing to non-optimal design of ITS. The results also indicated that that the annual energy consumption increased by 11% and the energy cost dropped by 50% compared to the case when no ITS is installed (Nassif, 2014 b).

The overall findings in this article displayed and emphasized the potential ice thermal storage technology holds in efforts of reducing energy costs when properly optimized.

2.8 Genetic Algorithms: An Overview

This article is about and was included due to its role on the insight provided on genetic algorithms. John Holland developed genetic algorithms in order to understand phenomenon of evolution in nature. From there this phenomenon was applied to computer systems. The central idea behind the development of genetic algorithms lied within the feature of evolution in problems that needed deep search in discovering an answer. The general process on how to solve a problem saw a change once the idea was discovered that different outcomes of a problem could be solved by the evolution of a solution. The advancement of this theory involved one solution branching off into numerous solutions in a continuing process and this created a way to solve many types of complex problems. As computer systems used for genetic algorithms began to evolve a viable question on exactly how they work did also. Genetic algorithms in a computer system were described as complex search programs that worked by setting an objective function, followed by the sorting of parameters needed to achieve and make the objective function work. From here, many outcomes are formed from the parameters and the system finds solutions through constant generations and iterations of the program until the most optimal solution is found. The aggressive and dynamic style of seeking the optimal result to the problem allows genetic algorithms to be categorized as a very effective as well as efficient optimization tool. All in all, this article was useful in the understanding of genetic algorithms as it pertains to the use of the genetic algorithm optimization tool that will be used in the discussions and work of this thesis.

CHAPTER 3

Simulations and Exploratory Research

3.1 Overview

The use of the energy simulation model and MatLab are the key components utilized in order to test ice thermal storage technology in this research. For the energy simulation model, it was decided to use the software called eQuest. EQuest is a building energy simulation software tool and MatLab is a unique programming language with a genetic algorithm feature that allows the program to solve for optimization. The building that the simulations are run for is an office research building with four floors. The tests are run for locations all across the United States and consist of a wide range of ASHRAE climate zones. This includes climate zones from both ends of the spectrum, zones with hot, dry weather as well as occasionally cold, wet weather regions, and any possibilities in between. A total of ten different locations are represented in the study.

3.2 Recommended Process

Below in Figure 3 is the developed algorithm for the process in the design of the variables needed in optimizing the implementation of ice thermal storage technology for commercial buildings. In this order of processes the program is given inputs and the program continues to run until the most optimal results have been attained. The procedure begins by retrieving the hourly cooling loads from the simulation program, for this study eQuest was used. From there, the utility cost rate structure is set and the outdoor air conditions are simulated and uploaded into MatLab. As the next steps takes place the program runs and begins its search for optimal design of the output variables and continues to run again and again to the best results are produced. During this period cost calculations for both ITS and no ITS cases are found for various factors including annual energy costs, & annual energy consumption just to name a few.

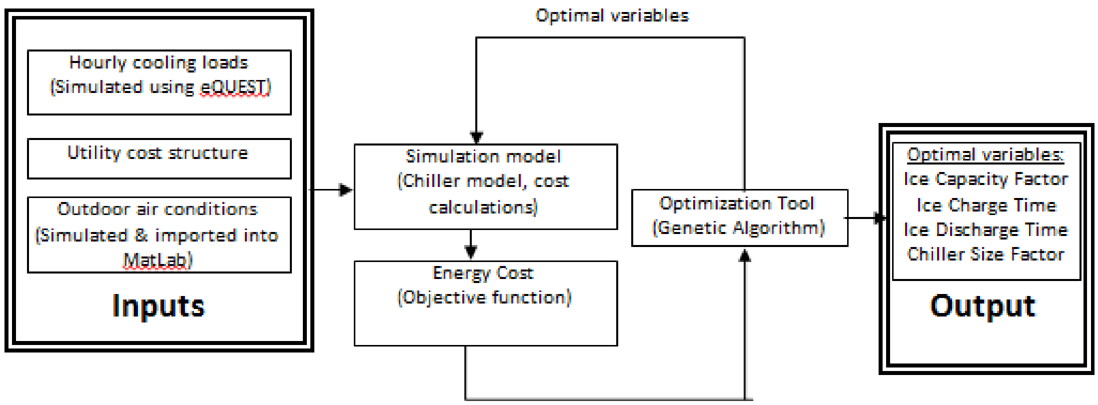

Figure 3 The developed and recommended optimization tool in the design of the ITS system.

3.3 Programs and Models

3.3.1 Simulation model. The simulation model developed in this study used the skillset offered by the eQuest energy simulation software to simulate the cooling loads throughout the ten test locations selected. The responsibility of eQuest as it pertains to this research is to gather and obtain vital information for use in the MatLab programs. This is done via the internet and simulations. The weather data for the location is downloaded into eQuest and once that is complete, the software simulates the cooling loads for the entire design year. From the energy simulations for the building for the year, eQuest provides hourly results for the entire simulated year. These hourly results for the year include: the required cooling load, the outside wet bulb temperature, and the outside dry bulb temperature. From this, MatLab is able to upload these results about the location and the location's weather effects on the cooling of the building and display the results for the monthly energy cost as well as the monthly energy consumption for the building with the implementation of ice thermal storage.

3.3.2 MatLab models. The MatLab program coding developed specifically for this research consists of three separate programs and ranges depending upon the desired outcome and results. There is a MatLab program written specifically for the chiller. The chiller model is the code directly related to and used for the chiller design. The program has information for the chiller, about its rating capacity, chiller power, chiller efficiency, and various temperatures of water that is in flow throughout the chiller. Information from the chiller model is read into the other main program models when data about the chiller is requested. The other two MatLab programs are the two main program models. The biggest differences in the two main program models is first how the input variables are obtained, and second the process in which the results are established. One main program model reads the input variables assigned and provides output results; while the other main program model is given a range for the input variables and the genetic algorithm allows the program to find the optimum output results in the range of input variables. The code will be explained in more depth and detail moving forward.

3.4 EQuest Process

EQuest provides a number of tools for building simulations. It allows the ability to test ‘what if’ scenarios and attain useful information before making any hasty decisions without any type of data to backup theories. To start eQuest, a building creation wizard assists in uploading the building into the program. From there many unique features in the program provide feedback on the building performance and how altering any technology or other aspect of the building can affect the building performance wise and its associated energy needs.

3.4.1 Building creation wizard. The building creation wizard for eQuest can be utilized in two approaches. When starting a project in eQuest there is the option of starting the building creation wizard through the schematic design wizard or either the design development wizard. Both building wizards are useful and helpful but depending on the stage and how much information on the building one has would determine which wizard would be most suitable. The schematic design wizard is most beneficial in the early design phases and when information on the building is limited. This is usually a wizard used for small, simple structures for an assignment pertaining to the building's internal load and/or HVAC equipment. The more advanced and detailed wizard would be the design development wizard. This wizard provides a more detailed design and requires more information on the building. In this setting one would input larger and very complicated assemblies, resulting in a cutting-edge HVAC system and more detailed internal loads.

3.4.2 Uploading the building via the wizard. The process of uploading the building into eQuest through the building creation wizard is an easy and simple yet extensive task. The wizard requests various, specific information about the building and it is very important as it all can affect and make a difference on the outcome of the simulation results. In the eQuest schematic design wizard there consists of forty one different screens of input concerning the building information. Figure 4 shows one screen and some of the general input information requested about the building as it is in the process of being uploaded into eQuest by the schematic design wizard. This figure displays the first prompt screen of the schematic design wizard in eQuest. The very first input screen in the wizard is where general information is provided regarding the building. Here information like: building type, location, utility and electric rates, area and floors, and basic heating and cooling measures is provided. It is here that the location is specified and later the location's weather data uploads. The type of data that the wizard request is wide ranging and works its way through all aspects of the building. Some of the categories about the building information that the wizard screens require include: general information, building footprint, building envelope, building interior, doors, windows, room information, lighting loads, building operational time, electrical and HVAC information, and many others. The biggest and possibly one the most important parts in this process is the HVAC equipment. Multiple screens are devoted to this as it gets very thorough and many of the simulations are for cooling and discovering loads for HVAC equipment. A unique aspect about this schematic design wizard is the ability to skip and leave some things unchanged. Not all fields throughout screens have to be altered and default choices can be left filled in. Also according to some prior answers some screens are automatically skipped and passed by.

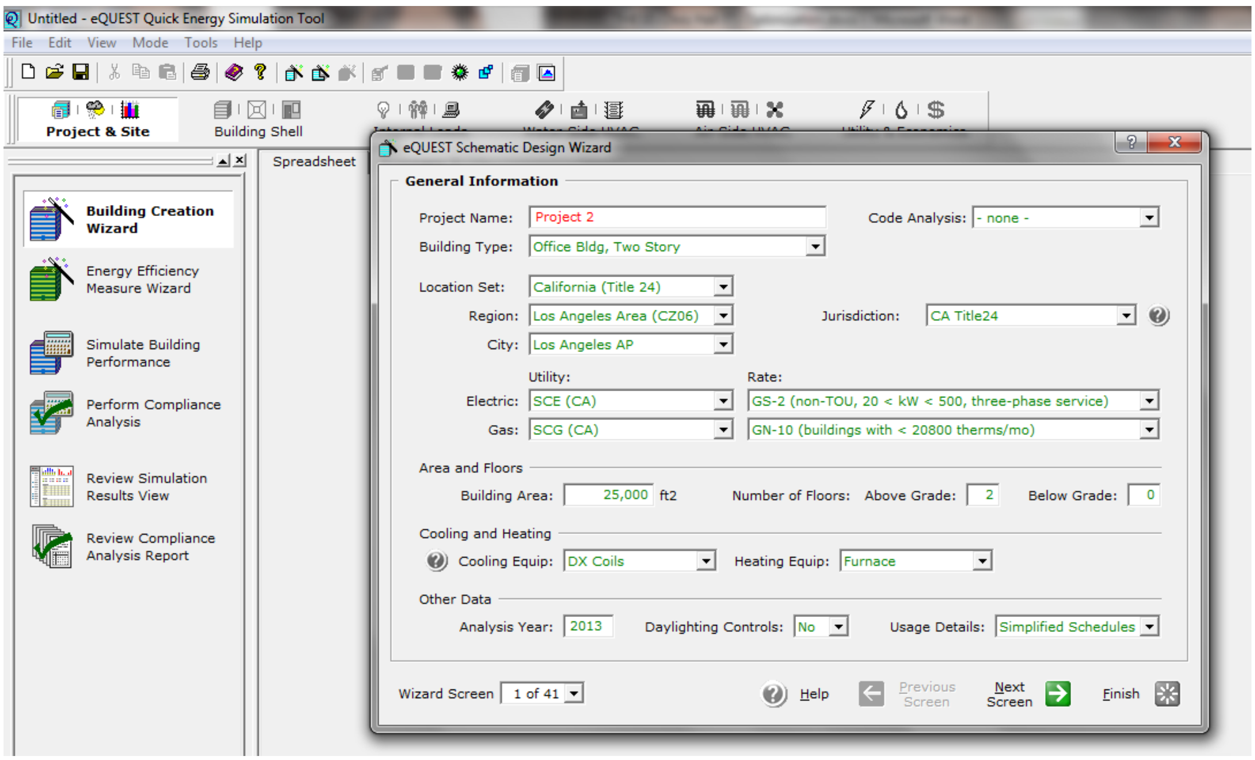

Figure 4 One screen of building input information for the eQuest schematic design wizard.

3.4.3 EQuest features and functions. After the building and all of its information is uploaded into eQuest, the system runs through a process where all files are loaded and each component input throughout the wizard is accounted for and administered into the eQuest file. From here the building is available in eQuest and there are some features and functions that are accessible to users. A digital model of the building is now obtainable because of the building footprint that was input during the wizard process. The building footprint consisted of real working floor plan drawings which, once uploaded, made the digital model of the building possible in eQuest. The digital model includes a 2-D geometry view as well as a 3-D geometry that is of a perspective angle. Below Figure 5 provides a look at the test building in this study uploaded into eQuest and displayed in a two-dimensional view.

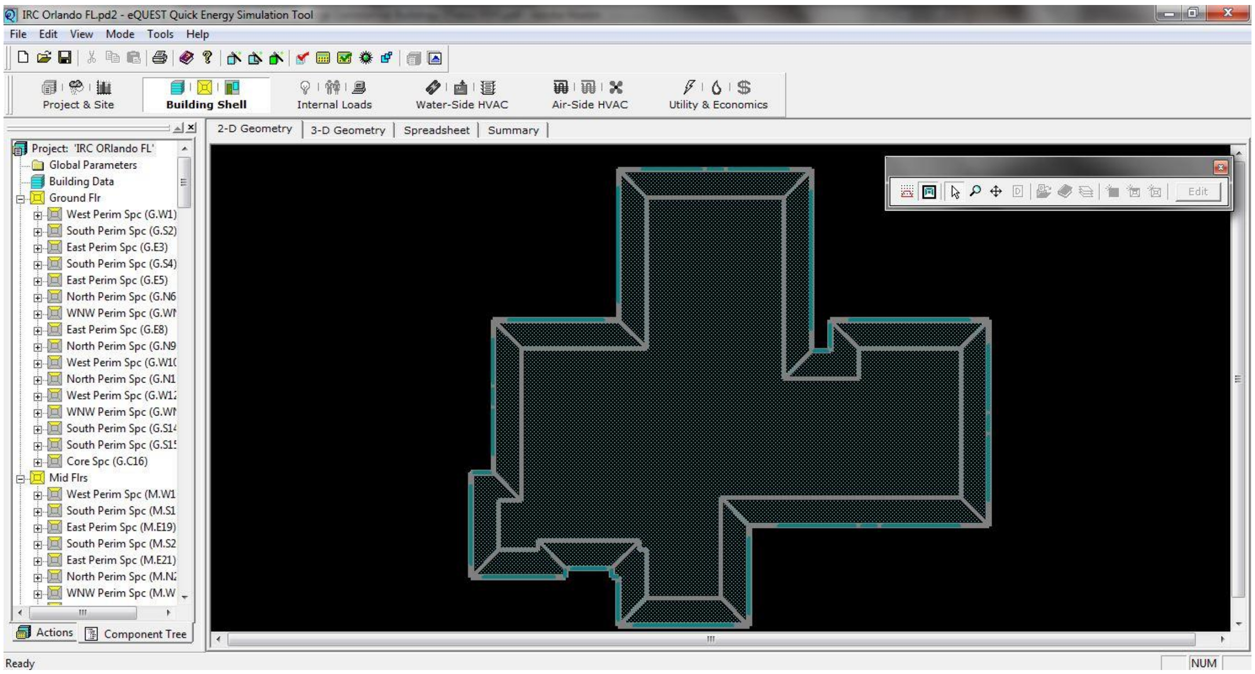

Figure 5 A two-dimensional digital view of the test building uploaded into eQuest.

Some other tools in eQuest come from the energy efficiency measure wizard, the ability to perform compliance analyses, and simulating the building performance. One very interesting energy savings measure that the eQuest software provides is in the program's energy efficiency measures wizard. Here, aspects of the building anywhere from the building envelope, internal loads, HVAC system, all the way to the site and building can be altered and tested up against the original baseline design uploaded initially during the wizard phase. This wizard is unique in its ability to allow for multiple tests run at once. In the end each test can be compared and judged for possible energy savings. Finally simulating the performance of the building is done to provide a very detailed report of the building's operational efficiency from an energy standpoint with many different documents, tables, and graphs of numerous reports. The simulation of the building performance tool is the key feature for this research. EQuest was used to perform this simulation task and following this task, the proposed MatLab program was developed in order to determine the ITS optimal design.

3.4.4 Simulating building performance. This is the final process in eQuest before the results are displayed and ultimately exported for use into MatLab. The simulation of the building performance offers a key to unlock an infinite amount of information on the building. Some items found include the reports for comparison-runs, single-runs, and parametric-runs. Inside of these there are the graphs and tables for monthly total energy consumption, annual and monthly utility bills, and even life-cycle summaries and graphs. The key takeaway and result of simulating the building performance as it is associated with this research lies in the hourly results for the calendar year. Provided are results for the cooling load, and dry and wet bulb outdoor temperatures for that particular location. Results are for every hour of the day and every day of the entire year, which is approximately 8,760 readings for each result type, making the study very precise and accurate. These hourly results are read into excel for viewing and from there imported into MatLab.

3.5 Developed MatLab Program Code

The MatLab program is the last piece to the ice thermal storage technology's optimization experiment. EQuest serves as the chosen method for the simulation model and to seek out vital background information and access weather and building loads for test locations. The MatLab program uses all of this information to optimize the ultimate capacity of efficiency that ice thermal storage technology can achieve. The rest of this section will explain in detail the design of the MatLab contribution to this experiment. Finally the code in MatLab will be displayed and dissected by major sections.

3.5.1 Input variables. The code for MatLab is what serves in finding the savings results for ice thermal storage technology. In starting this process, it is essential that the program is given some input information. Some of this information is read from the previously explained eQuest program, while others are still required and read directly in to the program from the user. Below Figure 6 is a display of the input portion of the code in MatLab.

```
clear all
%% Read problem variables
data= xlsread('Ice Thermal Storage.xlsx','Variables','C2:C5');
data(any(isnan(data),2),:)=[];
IceCapacity=data(1); %IceCapacity,
IceChargeTime=data(2);%Ice Charge time,
IceDischargeTime=data(3);%IceDischarge ChargeTime,
ChillerSizeFactor=data(4);%Chiller size
%% Given Information
```

Figure 6 Code from the MatLab program that references the input variables.

Here the figure shows the first few lines of code of the program that consists of the program's input variables. There are four variables that are input by the user: ice capacity factor, ice charge time, ice discharge time, and chiller size factor. The ice capacity factor serves as a variable for the input time or amount of hours that the ice thermal storage system will need to charge for full capacity. The variable for ice charge time is very simple. The declaring and input of this variable sets the time in which charging of the ice thermal storage system will commence. Ice discharge time for the system is the variable that tells the system to stop and ultimately shuts the chiller off altogether. When the discharge time period begins cooling of the building is done by the ITS system and the chiller remains inactive for as long as the ITS system has an adequate amount of ice to handle the load of cooling in the building. Finally, the chiller size factor variable is input to set how much the chiller will be oversized. Oversizing of the chiller is a safety measure and is done so in order to ensure the chiller would be operable in a worst possible case than originally designed for. These variables are the key components that effect the desired outcome results, energy cost and energy consumption.

3.5.2 Utility rate structure. This section of code is primarily related to the outcome and calculating of cost. Figure 7 illustrates the segment of code related directly to the utility rate structure. This includes declaring the official peak time period, the cost for energy consumption during on-peak time periods, off-peak time periods, and the peak cost. The utility rate structure is a component of the code that is unchanging for this research. For this study a basic, standard utility rate structure was kept constant for all test locations in order to compare ITS results and cost savings strictly due to location and weather. In future cases this portion of code would change and be read in by the user. The utility rate structure is generated and charged by a location's power company. This variable is one that would change from location to location and affect cost savings depending upon local utility rates.

```
% Utility Cost
PeakTime=[12,17];
OffPeak=(0.04181+0.01539);
OnPeak=0.007920+0.039580;
PeakCost=9.05;

```

Figure 7 This piece of code shows the introduction of the utility rate structure into the program.

3.5.3 Location weather data. Figure 8 below demonstrates the following lines of code pertaining to the import of weather data and cooling loads. This part of the program imports the weather data and cooling loads from the eQuest program. Variables are then established to set for the required cooling loads and dry and wet bulb temperatures. The data that is imported from eQuest consist of the 8,760 readings from the hourly simulation for the year. This was previously explained throughout the Simulating Building Performance subsection of the EQuest Process in chapter 3 section 4.

```
% Read load and Outdoor air conditions
[~, ~, raw] = xlsread('Ice Thermal Storage.xlsx','HourlyLoad','B3:D9000');
eQuestData = reshape([raw{:}],size(raw));
eQuestData(any(isnan(eQuestData),2),:)=[];
q=eQuestData(:,1)/12000; % to cover to tons
to=eQuestData(:,3);
twb=eQuestData(:,2);

```

Figure 8 The lines of code displaying the import of the weather data & cooling loads from eQuest into MatLab.

3.5.4 Chiller and ice thermal storage tank capacities. The design information is a small section of code in the ITS MatLab program but carries a big title as it is important that both the chiller and ITS tanks are designed and sized appropriately. Figure 9 displays these two very important lines of code. In optimizing the ice thermal storage units, under sizing these two components would cost more in the long run, while oversizing the two would cost a lot of money initially and be a huge waste. Here in just two lines of code the chiller and size of the ITS tanks are designed based upon the maximum cooling load reported from eQuest. The highest required cooling load given from eQuest is multiplied by the user input chiller size factor to give the chiller size in tons. Once the chiller is sized, it is taken and multiplied by the input ice capacity factor to determine the maximum capacity of the ice storage tanks sized in ton-hours. If designed correctly the chiller would be sized perfectly to cover the entire cooling load reported from eQuest and any possible worst case scenario. The sizing of the ice thermal storage tanks would be considered to be designed correctly if the cooling during the on-peak time periods are accounted for entirely and it is never necessary that the chiller be turned on during any on-peak time period, thereby incurring no peak costs for on-peak time.

```
%Design information (Calculated from eQuest)
qomax=max(q)*ChillerSizeFactor;%design chiller nominal load
CAP=qomax*IceCapacity; %Capcity of Ice Storage in Tons
```

Figure 9 This code from MatLab is needed for the design of the chiller and ITS tank sizes.

3.5.5 Operation of the chiller and ITS systems. This last part of code from the program is the biggest and most complex. The most important part of the code is shown in Figure 10. The rest of the code in MatLab is written for energy use calculations and different periods of the year and processes of the chiller, as well as ice charging periods, discharging periods, and normal operation of the cooling system including the chiller. During these different stages the program is running iterations for the 8,760 hourly cooling loads, and temperatures introduced from eQuest. For the different time periods, the code is running and telling the variables what to do and what data to store as it runs through the entire year, day by day. Finally at the end of the code there are outputs for the results and also figures to display necessary graphs portraying the results. Outputs for the data show the input ice capacity factor, the ice charge time, the summation of the monthly cost, and the summation of the monthly energy consumption. The first two outputs are simply designed to reiterate the input and are compared to how it affected the last two outputs, energy cost and consumption. Energy cost and consumption are the most important and cost being the bigger importance of the two.

```
D=1;
%% Calcuation
IceStorage=0;
for i=1:size(q,1)
    I(i)=i;
    Days=ceil((I(i)/24))-1;
    Qdisch(i)=0;
    Qch(i)=0;
    Qchil(i)=0;
    [e,Pxx(i),Q(i)]=ChillerModel(q(i),qomax,25,twb(i)+8); % to find Q

```

Figure 10 The last part of code begins the process of optimizing the system & energy calculations.

3.5.6 Genetic algorithm optimization model. The genetic algorithm optimization model is the other MatLab program main model that is used in finding the optimum results for the ITS technology. Figure 11 shows an optimization process being run for the office building being tested in the Greensboro, North Carolina location. This program reads in its input variables in a different method than previously explained for the main model code. Also the output for this model is found in a slightly different process because the program is not simply reading the inputs and presenting the corresponding outputs.

Here in this program the genetic algorithm is given a range of possibilities and from there the optimization tool finds the most efficient outputs that would fit and work comfortably with the known constraints. This model is the best of the two models to get a very close and accurate result of optimization, while the other model displays more data and gives more to work with and a way to test individual inputs. It is a good idea to use both models in combination and gain optimal results.

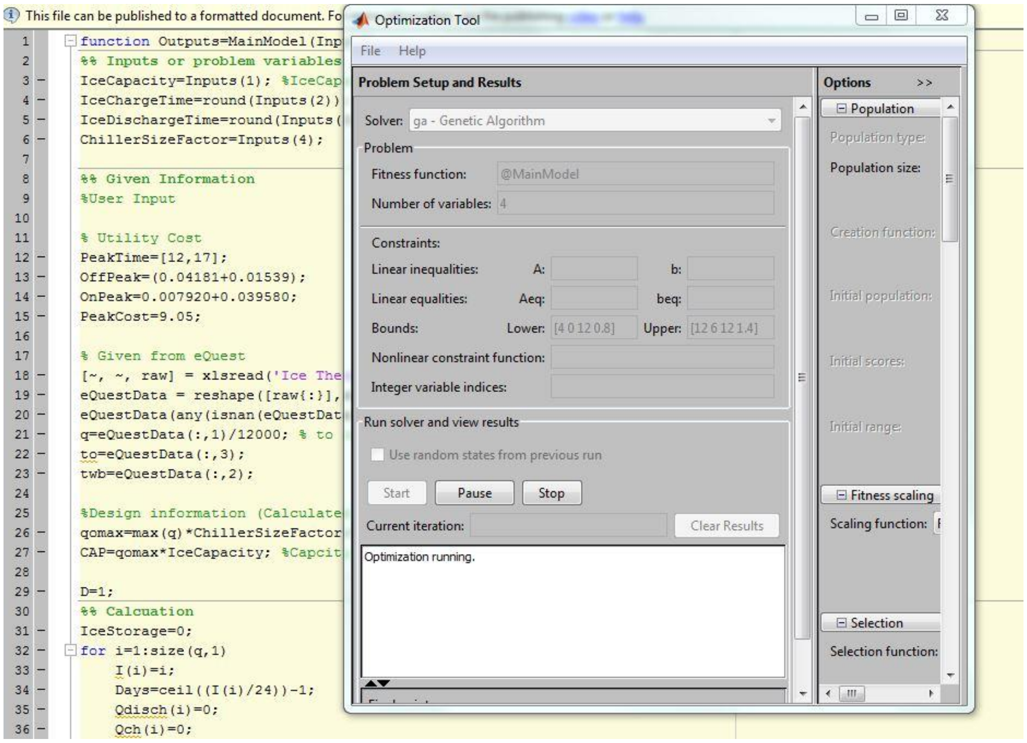

Figure 11 Optimization tool running in MatLab finding the optimal results for Greensboro, NC.

3.6 Building Description

The office building referred to throughout the reading is the same one used in every tested location. This was done to compare savings of ice thermal storage implementation in the various climate locations. The office building used in this research study was obtained from the campus of a university in Greensboro, North Carolina. It is the research office building known as the Edward B. Fort Interdisciplinary Research Center, or IRC, located on the campus of The North Carolina Agricultural and Technical State University. A real-time view of the building can be seen in Figure 12 below.

Figure 12 A live look at the Interdisciplinary Research Center in Greensboro, NC.

3.6.1 Brief building history. In the early 1950's is when the construction of the current IRC building first took place. Beginning in 1950 and all the way up until around 1991 this building was home to the library of North Carolina A&T State University campus students. For over 40 years the building was known to be the campus' Bluford Library. It was in 1991 that the Library moved and the building became vacant. Upon this occurrence the building saw extensive renovations and ultimately was transformed into a research facility for the campus faculty and students. It was named after Dr. Edward B. Fort who was the eighth chancellor of NC A&T State University, serving from 1981 to 1999.

3.6.2 IRC design. Today, the IRC houses research laboratories as well as offices for the Division of Research and Economic Development. Figure 13 displays a view of the building's central atrium that the facility is organized around. The atrium also has a monumental staircase extending from the first to fourth floors with a large central skylight. Inside the building there are a total of four floors, consisting of approximately 77,000 square feet of space. Throughout the building there are numerous types of spaces that can be found including: offices, research laboratories, storage space, some conference and meeting rooms, and of course bathrooms. The biggest reason this building is ideal for the simulations lies within the building's age. Although it has been renovated, originally built in the 1950's, its old structure lines up perfectly with typical commercial buildings that generally need improvements.

Figure 13 An interior view of the IRC and the central atrium leading up to the large skylight.

3.7 Methodology

3.7.1 Preceding research. The idea behind this investigation into ice thermal storage was to test its efficiency and effectiveness in numerous climates and environments. The original study was one where the opportunity was present to work on and it took place for an office building located and tested near Orlando, Florida. That study provided detailed simulations for the particular office building in Florida. The study considered the effect of the ice thermal storage technology on the building's chiller performance and any associated energy cost. The results of that initial study demonstrated the cost saving achieved from optimal ice thermal storage design. With the success of that prior research I was able to help gather and the intrigue to find an answer to just how effective and beneficial ice thermal storage technology can become in the enhancement of current and future buildings in energy cost savings, this study developed and I was able to take it on as my thesis and carry it out for further discovery. From here, the research blossomed into a study of the technology in at least one of every ASHRAE climate zone location.

3.7.2 ASHRAE climate zones. Local weather as well as a region's climate makes a substantial difference in the separation and sorting of the map into what are recognized by ASHRAE as climate zones. A graphic of the United States shaded and separated into ASHRAE's recognized climate zones can be seen in Figure 14. Building codes require a structure to meet certain R-values to achieve a specific level of efficiency. The climate zone plays a big role in determining what the minimum R-value has to be for a specific region. Additionally, each state or local code body may be at differing levels of adoption of energy codes.

The climate zones are made up of the typical weather patterns observed over time in the perspective regions. Based upon ASHRAE 90.1 there are eight recognized climate zones and three possible subtypes throughout the zones. The ASHRAE map of the climate zones shows the breakdown of each zone and the subtypes. The three subtypes are labeled at the top of the map and specify whether that region in the zone is either moist, dry, or marine. Zone 1 is a very hot, dry, and humid region. This zone can be found the furthest south in Florida and also includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands. In zone 2 the region is known to be hot, humid, and on some occasions dry. Zone 3 is typically warm, dry, and depending on the location either humid or marine. Zone 4 is characterized as mixed and has locations that are humid, dry, and marine. Moving further north, in zone 5 the climate is cool with differences of being humid, dry, and marine. Zone 6 is known for being cold and both humid and dry. Zone 7 is the zone that is very cold and visibly furthest north on the map. The last zone is zone 8, which is not visible on the map. Zone 8 is the subarctic region with locations such as Alaska.

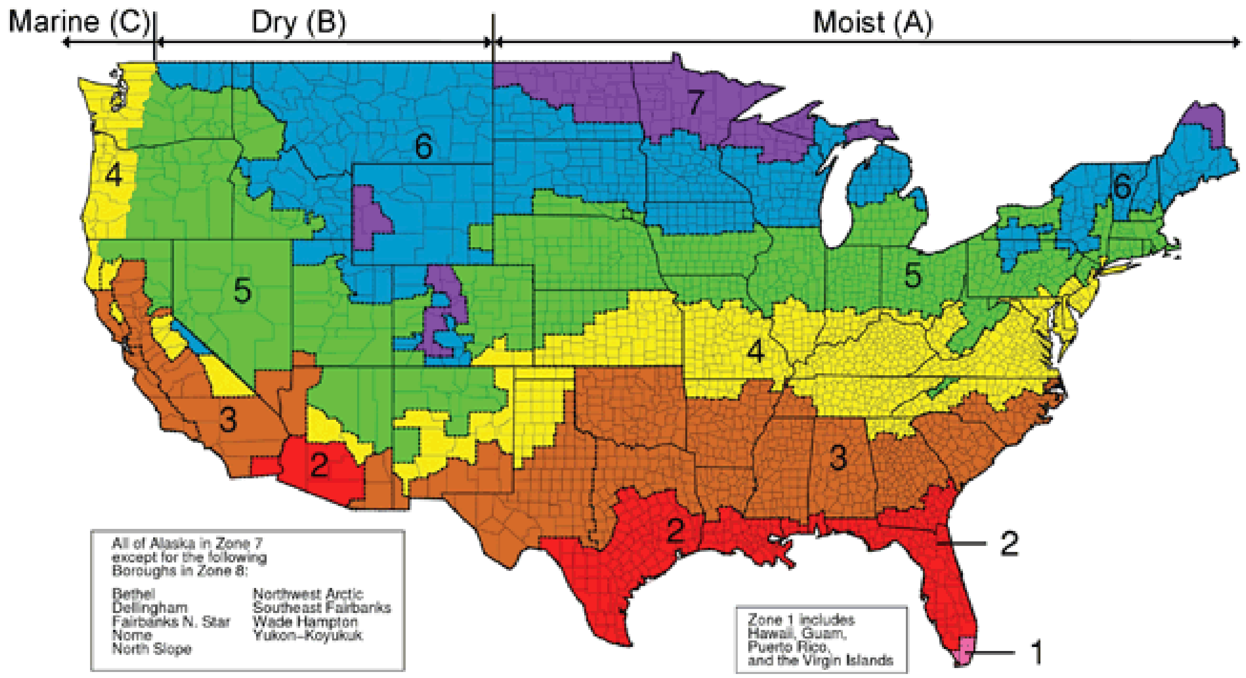

Figure 14 A map and graphic of ASHRAE 90.1 Climate Zones.

3.7.3 Location selection. In determining the test locations for this research it was decided that every climate zone would be represented. Finally a total of ten test locations were decided upon. Throughout the climate zones major cities were chosen at random, while in widespread regions the selection was made to keep the locations spread out and well balanced. Also each subtype of climate zones was purposely represented in the study. As a result there were some zones that were represented more than once in the location selection.

The states represented in the experiment came from Florida, North Carolina, Pennsylvania, Maine, Texas, Wisconsin, Arizona, California, and Washington. The state of Florida was actually chosen to be represented twice due to it having a small region labeled as a zone 1 climate, while its primary designation consist of being marked as zone 2. From zone 1, testing was held in Miami, Florida, in zone 2 this region was represented by Orlando, Florida as well as Phoenix, Arizona. The primary reason zone 2 was represented twice is because the two city locations lie within two different subtypes of climate zones. In Orlando, Florida zone 2 is under subtype A, which is moist. Located in Phoenix, Arizona zone 2 is categorized as climate zone subtype B, known to be dry. In zone 3 the location was Dallas, Texas and also San Diego, California. This was also due to differing climate zone subtypes. In Dallas, Texas the climate subtype is type A, moist, and in San Diego, California its climate zone subtype is type C, or marine. Zone 4 consisted of Greensboro, North Carolina which has a moist subtype A, as well as Seattle, Washington, having a marine subtype C. Zone 5 is tested in Philadelphia, Pennsylvania, zone 6 in Green Bay, Wisconsin, and zone 7 in Portland, Maine. The overall selection across the map allowed for an even spread and well balanced selection of location points, while staying in major cities for weather data purposes.

CHAPTER 4

Results and Findings

4.1 Overview

The energy cost savings that Ice Thermal Storage technology can provide has been well documented. This study was developed for the research purposes of comparing and analyzing the savings and benefits of using Ice Thermal Storage technology in different types of weather and climate regions throughout the United States. In the process of investigating the use of ice thermal storage technology in these various climate regions, a program was also developed to optimize the design of ice thermal storage dependent upon the location and that region's climate, the building's make-up, and the amount of cooling needed. Results for the experimented climate regions show, for the span of a year, the energy consumption in kWh for the building as well as the energy cost in dollars. With these output results the most optimal design criteria for ice thermal storage to run effectively and efficiently is determined. This in turn can lead to energy cost savings.

4.2 Research Test Results

The results obtained in the research of the locations were done so initially by the user manually entering input data designed for the ITS technology. After doing so, the MatLab program was able to read the respective inputs and display the requested output results. This method was done and repeated numerous times for an infinite number of possibilities for the input variables. This was carried out for each location and evaluated. It is with these manual results that observations were made and from there parameters were established in assigning input variable ranges for the proposed optimization model that was developed. These optimal results for the test locations will be displayed later in the research. The locations in which the ice thermal storage technology was tested and optimized consisted of seven different climate zones out of eight possible ASHRAE recognized climate zones. In addition to this, there are three subtypes that the climate regions are divided up into based upon the regions being moist, dry, or marine. The following results are reported and separated by the region's subtype.

4.2.1 Climate region subtype A: Moist. The biggest of the climate region subtypes consist of climate zones that are moist regions. ASHRAE has recognized over half of the United States' climate zones as moist. This region is known for being very moist across the map. Throughout this region there are seven climate zones represented proving there are very differing and diversifying climates in this region subtype of the United States. For this reason, there are seven locations tested in this moist subtype region, one being represented by each ASHRAE recognized climate zone. Stretching across the entire climate region subtype and accounting for each zone, these cities include: Miami, Orlando, Dallas, Greensboro, Philadelphia, Green Bay, and Portland.

4.2.1.1 Miami, Florida. Climate zone 1 is a very hot, dry, and humid region and was evaluated in Miami, Florida. This type of climate zone is primarily found in the farthest southern tip of Florida and also recognized in Hawaii, Guam, Puerto Rico, and the Virgin Islands. The following Table 1 shows a portion of some manual results recorded from ice thermal storage testing for the IRC building if located in Miami, Florida. The results show the differences and effects multiple ITS design input variables made on the outcomes of the building's energy consumption, as well as its energy cost for the year. For the manual results the key factors that made a difference on the outcomes were the input ice capacity factor and ice charge time. Ice discharge time was always a given due to the time the ITS system needed to begin cooling during the on peak period of the day. Finally, the chiller size factor remained constant during the manual testing, providing a twenty percent safety factor. The complete table with all other manual results for this location can be found in the appendix.

Table 1

Some manual results for ice thermal storage use in Miami, Florida.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		22927	301,200
4	0	12	1.2		22133	298650
4	1	12	1.2		22133	298650
4	2	12	1.2		21943	298070
5	23	12	1.2		17257	301700
5	0	12	1.2		17096	29888
5	1	12	1.2		17096	29888
5	2	12	1.2		17611	298330
6	23	12	1.2		17268	301890
6	0	12	1.2		17120	299310
6	1	12	1.2		17120	299310
6	2	12	1.2		17085	298690
7	23	12	1.2		17281	302120
7	0	12	1.2		17134	299550
7	1	12	1.2		17134	299550
7	2	12	1.2		17096	298870
8	23	12	1.2		17296	302380
8	0	12	1.2		17147	299780
8	1	12	1.2		17147	299780
8	2	12	1.2		17111	299140
9	23	12	1.2		17310	302610
9	0	12	1.2		17160	300000
9	1	12	1.2		17160	300000
9	2	12	1.2		17123	299350

The table shows results starting with an ITS system ice capacity factor of four. Testing was done for an ice capacity factor that ran from a minimum of four all the way up to a maximum of twelve. For each ice capacity factor size an individual run was tested for ice charge times of twenty-three, zero, one, and two. These ice charge times are the times of the day in which the ice charging period is set to begin; twenty three representing eleven at night, zero is midnight, and so on. The most consistent of the results proved to be the ITS design with an ice capacity factor of eight. From here the results were taken and used in the genetic algorithm to find the most optimum results where even the chiller size factor was open to being adjusted and changed along with the ice capacity factor and ice charge time. The most optimal results presented an energy consumption of 296,030 kWh for the year. With that amount of energy consumed the energy cost for the year in Miami, Florida just from the cooling after simulation was a mere $16,933. The optimal results that were gathered using the genetic algorithm optimization tool will be explained in a later section, following the other test location results. This process continued for the other nine test locations and everything was completed manually as a course of trial and error. Moving forward the results for other locations will be stated along with the differences in the outcome results.

4.2.1.2 Orlando, Florida. Moving forward into climate zone 2, this testing also took place in the state of Florida. Climate zone 2 was held in Orlando, Florida; located square in the middle of the state as well as the most central part of this climate zone. This climate zone spans west as far as Texas in climate subtype A, all the way back east and up to southern parts of Georgia. There is also a portion of Phoenix, Arizona that is considered to be categorized as climate zone 2, but falls under climate subtype B. This will be discussed in a later section for the dry subtype B. The outcome of results for testing in Orlando, Florida showed the differences in the climate zones effect on a building's energy usage and cost. Both Orlando and Miami, located in Florida but falling in different climate zones, have uniquely differing weather and climate to the extent that cooling during the summer resulted in a substantial reduction in energy cost and consumption for the building while located in Orlando. Below Table 2 shows a portion of the manual test results simulated in Orlando, Florida. The complete table with all other manual results for this location can be found in the appendix. The only input differences in these results in comparison to the previous tests were the location and the location's weather data information.

It is immediately evident that the results became altered and it was due to the difference in climate data provided for Orlando.

Table 2

The output readings for climate zone 2 located in Orlando, Florida.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		17395	264,800
4	0	12	1.2		18239	262280
4	1	12	1.2		18239	262280
4	2	12	1.2		17965	261970
5	23	12	1.2		15168	265170
5	0	12	1.2		15007	262360
5	1	12	1.2		15007	262360
5	2	12	1.2		15329	262210
6	23	12	1.2		15177	265330
6	0	12	1.2		15037	262890
6	1	12	1.2		15037	262890
6	2	12	1.2		15006	262340
7	23	12	1.2		15187	265520
7	0	12	1.2		15043	262990
7	1	12	1.2		15043	262990
7	2	12	1.2		15017	262530
8	23	12	1.2		15199	265720
8	0	12	1.2		15054	263180
8	1	12	1.2		15054	263180
8	2	12	1.2		15026	262700
9	23	12	1.2		15211	265920
9	0	12	1.2		15061	263310
9	1	12	1.2		15061	263310
9	2	12	1.2		15041	262950

The results in this location still proved a most consistent savings when an input capacity factor of 8 was assigned. The most optimal results presented an energy consumption of 259,340 kWh for the year. With that amount of energy consumed the energy cost for the year in Orlando, Florida just from the cooling after simulation was a mere $14,834. In obtaining these optimal results a range of inputs were set and used within the genetic algorithm to optimize the ice thermal storage design.

4.2.1.3 Dallas, Texas. The big state of Texas is home to three climate zones throughout the region. Texas lies within climate zone 2, the biggest portion being climate zone 3, and a small portion of north Texas that falls in the category of climate zone 4. The simulated tests for climate zone 3 occurred in Dallas, Texas. Climate zone 3 runs through southern sections of North Carolina and extends all the way over to Texas and Oklahoma. Another decent size region of climate zone 3 takes up a huge portion of California. The part of California that is labeled under climate zone 3 is categorized as climate subtype C and will be discussed in the future. The results from simulations in Dallas, Texas for climate zone 3 are shown throughout Table 3, which can be seen below.

Table 3

ITS results are shown partly for climate zone 3 in Dallas, Texas.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
8	23	12	1.2		12031	210330
8	0	12	1.2		11819	206620
8	1	12	1.2		11819	206620
8	2	12	1.2		11780	205940
9	23	12	1.2		12040	210490
9	0	12	1.2		11828	206790
9	1	12	1.2		11828	206790
9	2	12	1.2		11790	206110
10	23	12	1.2		12049	210660
10	0	12	1.2		11840	206990
10	1	12	1.2		11840	206990
10	2	12	1.2		11802	206320
11	23	12	1.2		12059	210820
11	0	12	1.2		11848	207140
11	1	12	1.2		11848	207140
11	2	12	1.2		11810	206470
12	23	12	1.2		12066	210940
12	0	12	1.2		11856	207280
12	1	12	1.2		11856	207280
12	2	12	1.2		11821	206660

Although the table shows the results for ice capacity factors ranging from eight to twelve, the initial testing was still done for capacity factors of ice starting at a minimum of four. The results displayed for simulations in Dallas, Texas are from higher ice capacity factor inputs. This is due to the observations drawn in the trial and error runs. The most consistent results were due to the higher ice capacity factors. It was indicated the best savings were the result of an ice capacity factor of 12. The most optimal results presented an energy consumption of 202,680 kWh for the year. With that amount of energy consumed the energy cost for the year in Dallas, Texas just from the cooling after simulation was a mere $11,593. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.1.4 Greensboro, North Carolina. The breakdown of North Carolina into climate zones is nearly half and half. The state of North Carolina is composed of climate zones 3 and 4. A very small division of North Carolina is considered to be climate zone 5. The section of North Carolina that makeup climate zone 3 is the south and south eastern parts of the state. The north and northwestern parts of North Carolina is categorized into climate zone 4, with the exception of the tiny section that is labeled under climate zone 5. For the testing of climate zone 4 in North Carolina a city location was chosen that was fitting due to the fact that the building resides there in reality. The testing for the building in climate zone 4 was actually recorded in Greensboro, North Carolina. This selection in North Carolina was made primarily for the fact that the building already resides in Greensboro. Another aspect that went into the location of Greensboro being chosen as the testing spot in North Carolina for climate zone 4 analysis was due to the city's well known unpredictable weather patterns and diverse climate. The findings below can be seen in Table 4 providing the results for ice thermal storage simulations for the Greensboro, North Carolina location. Climate zone 4 is a mixed climate zone that often sees many different weather patterns sometimes being humid, dry, and even marine. This is exactly the case when it is stated that Greensboro weather is typically unpredictable and very rare in that it is unchanging.

Table 4

Ice thermal storage results for testing in Greensboro, NC.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
8	23	12	1.2		8392	146710
8	0	12	1.2		8207	143470
8	1	12	1.2		8207	143470
8	2	12	1.2		8165	142740
9	23	12	1.2		8402	146880
9	0	12	1.2		8217	143660
9	1	12	1.2		8217	143660
9	2	12	1.2		8174	142900
10	23	12	1.2		8418	147160
10	0	12	1.2		8225	143800
10	1	12	1.2		8225	143800
10	2	12	1.2		8185	143090
11	23	12	1.2		8417	147150
11	0	12	1.2		8233	143940
11	1	12	1.2		8233	143940
11	2	12	1.2		8195	143260
12	23	12	1.2		8417	147150
12	0	12	1.2		8238	144020
12	1	12	1.2		8238	144020
12	2	12	1.2		8205	143420

The results for the simulations in climate zone 4 in Greensboro, North Carolina are the first that present a drop off in the amount of energy consumed. This also resulted in declining numbers for the cost of energy that it showed would be needed in cooling the building. This occurrence was ultimately proven to be due to the location and that location's climate. As the location has moved further north and into yet another climate zone the weather and climate has changed enormously. The amount of cooling needed in this type of climate is much lesser than that of any tested location that was observed and analyzed prior to this section. The observation made for climate zone 4 showed that there was a similarity in that of climate zone 3 testing. This location also seemed to be more cost effective with higher ice capacity factors. When simulations were run for high ice capacity factors it is shown that energy consumptions as well as energy cost were down on a consistent basis. Again the trial and error runs showed that the optimal results pointed towards an ice capacity factor of 12. The most optimal results presented an energy consumption of 140,460 kWh for the year. With that amount of energy consumed the energy cost for the year in Greensboro, North Carolina just from the cooling after simulation was a mere $8,035. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.1.5 Philadelphia, Pennsylvania. Climate zone 5 seemingly is the biggest of the eight climate zones recognized by ASHRAE. Climate zone 5 stretches across the entire width of the United States, west from California all the way to east in Rhode Island and Massachusetts; gracing the North, Midwest, and the West Coast. Throughout this stretch across the United States this climate zone 5 touches approximately twenty-four different states. This climate zone being characterized primarily as a cool climate will show to need a lot less cooling and therefore savings will prove to be least likely to be obtained than that of a warmer climate. For the evaluation of climate zone 5 the testing was done in Philadelphia, Pennsylvania. Philadelphia was a great choice for testing for its known cold, long winters. It was great to test the effectiveness of this technology in a city in the climate zone that doesn't always see a particularly long stretch of heat in summers. Philadelphia sees stretches of heat in the summer but also has periods where its summer can see cool days and times that cooling isn't necessarily needed. Testing in a city like this gives a look into the type of results that will be expected in even colder climates that were later tested. Table 5 shown below displays the output results collected for the trial and error readings taken in climate zone 5 located in Philadelphia, Pennsylvania. The results here are displayed for the midrange of results produced, due to the more consistent of results lying near the middle of the data. The complete table with all other manual results for this location can be found in the appendix. It is now becoming more and more evident that as the test locations move further and further north, energy cost and consumption will continue to decline. This is the cause of the direct relationship between the climate and the locations' need for cooling.

Table 5

The partial results for climate zone 5 in Philadelphia, Pennsylvania.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
7	23	12	1.2		7012	122580
7	0	12	1.2		6883	120320
7	1	12	1.2		6883	120320
7	2	12	1.2		6853	119810
8	23	12	1.2		7021	122750
8	0	12	1.2		6891	120470
8	1	12	1.2		6891	120470
8	2	12	1.2		6862	119960
9	23	12	1.2		7030	122910
9	0	12	1.2		6901	120650
9	1	12	1.2		6901	120650
9	2	12	1.2		6871	120120
10	23	12	1.2		7040	123070
10	0	12	1.2		6912	120840
10	1	12	1.2		6912	120840
10	2	12	1.2		6880	120280
11	23	12	1.2		7049	123230
11	0	12	1.2		6920	120970
11	1	12	1.2		6920	120970
11	2	12	1.2		6889	120440

The range of the results displayed provides outcomes for the testing in Philadelphia, Pennsylvania where ice capacity factors range from seven up to eleven. In this location of research the consistency lied within the ice capacity factor most closely provided as 9. The most optimal results presented an energy consumption of 118,450 kWh for the year. With that amount of energy consumed the energy cost for the year in Philadelphia, Pennsylvania just from the cooling after simulation was a mere $6,775. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.1.6 Green Bay, Wisconsin. Typical characteristics of climate zone 6 include being very cold, and at times even humid and dry. Climate zone 6 is located mostly within the north-west regions of the United States, while a few areas in the north-east also fall under this climate zone category. States like Montana, Wyoming, North and South Dakota, Minnesota, Wisconsin, New York, Vermont, and Maine are states that have climates that makeup climate zone 6. The test location for this climate zone was taken within the middle of climate zone 6 that stretches across the United States. Simulations for this zone were taken in the climate for the state of Wisconsin. Known for its very harsh and cold winters, Green Bay, Wisconsin was a perfect location to test the ice thermal storage design for a normally colder weather climate. The following Table 6 shows a portion of some manual results recorded from ice thermal storage testing for the IRC building if located in Green Bay, Wisconsin.

Table 6

Manual results from ITS testing in Green Bay, Wisconsin.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
8	23	12	1.2		4449	77784
8	0	12	1.2		4329	75677
8	1	12	1.2		4329	75677
8	2	12	1.2		4316	75446
9	23	12	1.2		4456	77899
9	0	12	1.2		4336	75803
9	1	12	1.2		4336	75803
9	2	12	1.2		4307	75299
10	23	12	1.2		4460	77969
10	0	12	1.2		4339	75857
10	1	12	1.2		4339	75857
10	2	12	1.2		4315	75432
11	23	12	1.2		4464	78046
11	0	12	1.2		4348	76006
11	1	12	1.2		4348	76006
11	2	12	1.2		4324	75586
12	23	12	1.2		4455	77889
12	0	12	1.2		4353	76095
12	1	12	1.2		4353	76095
12	2	12	1.2		4332	75740

The results here for Green Bay, Wisconsin continues to show the expected drop in cost and consumption of energy due to the lack of need for cooling. Colder climates require far less energy for cooling and therefore provide far smaller results. Output results for this climate zone location show there to be somewhat similar outputs for the different tested ice capacity factors. The lack of a demand for cooling can be attributed to this unwavering outcome in results even though inputs are diverse and changing. Still the final outcomes did display a focus where energy cost and consumption could be optimized. The most consistent and promising of results proved to be the ice capacity factor designation of 10. The most optimal results presented an energy consumption of 74,732 kWh for the year. With that amount of energy consumed the energy cost for the year in Green Bay, Wisconsin just from the cooling after simulation was a mere $4,275. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.1.7 Portland, Maine. The very tip and most northern part of the United States was selected for ice thermal storage technology testing to represent ASHRAE's climate zone 7. The results for this climate zone were gathered in Portland, Maine. States that are grouped into climate zone 7 are only partially grouped into this climate zone, including the state of Maine. Other states that falls under this category include: North Dakota, Minnesota, and Wisconsin. All 4 of these states are represented by climate zone 7, but only a portion of the state, generally the northern region. Climate zone 7 is the coldest of the represented and tested climate zones, albeit the most northern tested location. The findings below can be seen in Table 7 which provide the results for ice thermal storage simulations for the Portland, Maine location. The results here are displayed for the midrange to the backend of results produced, due to the more consistent of results lying near the middle of the data. The complete table with all other manual results for this location can be found in the appendix.

Table 7

Ice thermal Storage design output results for Portland, Maine.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
8	23	12	1.2		3960	69233
8	0	12	1.2		3888	67979
8	1	12	1.2		3888	67979
8	2	12	1.2		3860	67476
9	23	12	1.2		3968	69371
9	0	12	1.2		3896	68105
9	1	12	1.2		3896	68105
9	2	12	1.2		3868	67617
10	23	12	1.2		3976	69502
10	0	12	1.2		3901	68204
10	1	12	1.2		3901	68204
10	2	12	1.2		3876	67763
11	23	12	1.2		3983	69632
11	0	12	1.2		3908	68327
11	1	12	1.2		3908	68327
11	2	12	1.2		3884	67898
12	23	12	1.2		3997	69871
12	0	12	1.2		3916	68468
12	1	12	1.2		3916	68468
12	2	12	1.2		3890	68009

These results produced in Portland, Maine are most closely related to the previous findings presented for Green Bay, Wisconsin. Here the results have remained consistent and constant for the cold weather climate locations in that cooling lacking has caused limits on possible energy savings for these colder climate zones. Colder climates see a bigger portion of their energy consumption in heating costs and ice thermal storage cannot target that to provide any energy cost savings. In the testing here in Portland, Maine output results still showed a consistent, even spread throughout the ice capacity factors tested. The most consistent and promising of results also still proved to be the ice capacity factor designation of 10. The most optimal results presented an energy consumption of 66,614 kWh for the year. With that amount of energy consumed the energy cost for the year in Portland, Maine just from the cooling after simulation was a mere $3,810. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.2 Climate region subtype B: Dry. Climate region subtype B is the next biggest region subtype. This region subtype is characterized as dry and spans nearly half the amount of the United States as the moist climate region subtype A. In this climate region subtype there is four of the climate zones represented. Each climate zone in this subtype region is also represented throughout the previously discussed subtype A. Due to this reason only one location in this region subtype was chosen to be tested. For the dry climate region subtype the test location was selected to be simulated in Phoenix, Arizona for its much known dry desserts and mainly fierce hot summers.

4.2.2.1 Phoenix, Arizona. The city and state of Phoenix, Arizona fits the exact characteristics of the climate subtype B, which is generally known for being very dry. Phoenix is known for big desert areas and an overall ideal choice to result in great energy cost savings due to optimal design of this ice thermal storage technology. As earlier stated, the testing for the Phoenix location lies within climate zone 2. This portion of climate zone 2 that falls under the climate subtype B is very small and is only located within a small region of Arizona. The rest of and majority of climate zone 2 was inside of climate subtype A and consisted of states as far west as Texas in climate subtype A, all the way back east and up to southern parts of Georgia. This climate zone is primarily hot, humid, and dry and was discussed earlier in prior sections. Below Table 8 shows a portion of the manual test results simulated in Orlando, Florida. The outcome here again provided results that led to more consistency from midrange to the backend of the tested input variables. The complete table with all other manual results for this location can be found in the appendix.

Table 8

The output readings for climate zone 2 located in Phoenix, Arizona.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
8	23	12	1.2		11714	204790
8	0	12	1.2		11432	199860
8	1	12	1.2		11432	199860
8	2	12	1.2		11359	198590
9	23	12	1.2		11723	204950
9	0	12	1.2		11439	200000
9	1	12	1.2		11439	200000
9	2	12	1.2		11369	198760
10	23	12	1.2		11731	205090
10	0	12	1.2		11448	200140
10	1	12	1.2		11448	200140
10	2	12	1.2		11378	198920
11	23	12	1.2		11741	205260
11	0	12	1.2		11453	200230
11	1	12	1.2		11453	200230
11	2	12	1.2		11388	199090
12	23	12	1.2		11749	205400
12	0	12	1.2		11462	200390
12	1	12	1.2		11462	200390
12	2	12	1.2		11396	199230

It was most evident at the initial viewing of these results at the re-shifting of the outcome results. Here testing has changed to a new climate subtype, all while moving back to a far hotter climate. This has inevitably resulted into the output results shifting into increasing once again. The switch back to increases in the output results reaffirms the testing that took place earlier for climate zone 2 in subtype A, for Orlando, Florida. These results confirm that ice thermal storage can be very beneficial and provide cost savings all throughout locations of climate zone 2. The testing of ice capacity factors varied and showed most consistency the higher the factor. The most consistent and promising of results also still proved to be the ice capacity factor designation of 10. The most optimal results presented an energy consumption of 197,000 kWh for the year. With that amount of energy consumed the energy cost for the year in Phoenix, Arizona just from the cooling after simulation was a mere $11,269. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.3 Climate region subtype C: Marine. On the ASHRAE climate zone map the third and final climate region subtype is the subtype C which is known to be characterized as Marine. This climate region is very small in size and clips portions of a few states. The marine subtype C runs through a small piece of Washington, Oregon, and California; which is due to the nature of marine climate regions. Marine climate regions are essentially on the west coast, near the ocean coast, and consist of warm but not hot summers, and cool but not cold winters. There are three climate zones in this marine climate region subtype. The tests for this climate were simulated in the cities of San Diego, California and Seattle, Washington.

4.2.3.1 San Diego, California. The marine climate subtype C is not hard to miss due to its brief stint on the ASHRAE climate zone map. This climate subtype is home to just two climate zones and graces only three of the fifty states in the United States. For climate subtype C the first of two test locations was decided to be within climate zone 3. This series of manual test results took place in San Diego, California. In the marine climate subtype C the climate zone 3 is only located in the state of California. Here in this climate subtype along with the climate being warm and dry, the marine subtype makes this region's climate marine due to its relative closeness to the coast. The partial outcome for ITS testing in this marine climate subtype C can be viewed in Table 9 below. Full table results for all ice capacity factors that were tested for this location can be found in the appendix in the back for trial and error manual test results. For the first tested city in a marine climate subtype we see that the results still cater to a benefit for the usage of ice thermal storage but with a slight decline. This is due to a move from a dryer climate to a little more well-balanced climate that is marine and close to the coast. Moving forward it will be of interest to see how a test location will respond as the simulation moves further north into a higher, colder climate zone that is also marine in nature. This will be viewed and discussed in the following section for the last and final tested location following the results analysis.

Table 9

Some manual results for ice thermal storage use in San Diego, California.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
7	23	12	1.2		6347	110960
7	0	12	1.2		6277	109740
7	1	12	1.2		6277	109740
7	2	12	1.2		6257	109390
8	23	12	1.2		6357	111130
8	0	12	1.2		6287	109920
8	1	12	1.2		6287	109920
8	2	12	1.2		6267	109560
9	23	12	1.2		6365	111270
9	0	12	1.2		6296	110070
9	1	12	1.2		6296	110070
9	2	12	1.2		6274	109680
10	23	12	1.2		6374	111440
10	0	12	1.2		6304	110220
10	1	12	1.2		6304	110220
10	2	12	1.2		6283	109840
11	23	12	1.2		6384	111600
11	0	12	1.2		6313	110360
11	1	12	1.2		6313	110360
11	2	12	1.2		6292	110000

San Diego, California is another test location that turned out results that were expected. In this city costs were slightly under that of the other climate zone 3 test location, Dallas, Texas. This is believed to have been attributed to the fact that the climate for San Diego is slightly less intense than that of Dallas, although both cities are categorized inside of climate zone 3. Also the aspect of Dallas, Texas being inside climate subtype B where it is known for being dry in oppose to San Diego, California being located within climate subtype C and known for being marine. Here the testing for ice capacity factors was more reliable near the middle of the tested input variables. The most dependable of ice capacity factors were shown to be in the range of ice capacity factors tested at 9. The most optimal results presented an energy consumption of 109,370 kWh for the year. With that amount of energy consumed the energy cost for the year in San Diego, California just from the cooling after simulation was a mere $6,255. These optimal results were obtained using the genetic algorithm optimization tool.

4.2.3.2 Seattle, Washington. The tenth and final location for ice thermal storage testing was done and concluded in climate zone 4 for the marine climate subtype C. This climate zone is the second of the only two existing climate zones within this climate subtype. The other, climate zone 3, was recorded in San Diego, California and previously discussed earlier in the text. Here for climate zone 4 in the marine subtype the city location was selected to be Seattle, Washington. This location is the most northern tested site on the west coast and in the marine climate subtype. The partial outcome for ITS testing in this marine climate subtype C can be viewed in Table 10 below. Full table results for all ice capacity factors that were tested for this location can be found in the appendix in the back for trial and error manual test results. Climate zone 4 is a mixed climate zone that often sees many different weather patterns sometimes being humid, dry, and even marine. The results here are displayed for the end-range of results produced, due to the more consistent of results lying near the higher tested ice capacity factors in the data. It is now evident as the test locations move further and further north on the west coast that energy cost and consumption will also continue to decline. This is the cause of the direct relationship between the climate and the locations' need for cooling. However, here on the west coast the decline still exist although the climate zones are not as cold and frigid as the tested locations seen and observed over on the east coast.

Table 10

ITS results are shown partly for climate zone 3 in Seattle, Washington.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
8	23	12	1.2		2361	41281
8	0	12	1.2		2293	40092
8	1	12	1.2		2293	40092
8	2	12	1.2		2285	39939
9	23	12	1.2		2367	41379
9	0	12	1.2		2300	40196
9	1	12	1.2		2300	40196
9	2	12	1.2		2291	40059
10	23	12	1.2		2373	41489
10	0	12	1.2		2306	40311
10	1	12	1.2		2306	40311
10	2	12	1.2		2298	40172
11	23	12	1.2		2380	41612
11	0	12	1.2		2313	40428
11	1	12	1.2		2313	40428
11	2	12	1.2		2305	40293
12	23	12	1.2		2387	41733
12	0	12	1.2		2319	40548
12	1	12	1.2		2319	40548
12	2	12	1.2		2311	40402

The most obvious results drawn from the data produced here for the Seattle testing resides in the information for the location's energy costs and consumption. The results show the lowest of recorded data in any previous testing in all other locations. These outputs of lower values are very much expected because of the location of Seattle. The surprise lies within the amount of decline the output results incurred with respect to the location's climate zone. Although Seattle, Washington is located very far north, the city still is only categorized as a climate zone 4 designation, however the results for the city show an output that has declines for climates zones that are much colder and frigid. In this city the consistent results were in line with the higher ice capacity factors. The ice capacity factor tested for 10 is shown to be most optimal in Seattle and was further tested. The most optimal results presented an energy consumption of 39,600 kWh for the year. With that amount of energy consumed the energy cost for the year in

Seattle, Washington just from the cooling after simulation was a mere $2,360. These optimal results were obtained using the genetic algorithm optimization tool.

4.3 Test Location Non-Optimal Manual Results

4.3.1 Preliminary testing of locations. The previously discussed results found in the tables for the different cities are really broad and simply serve as a basis for the beginning research. These manual, non-optimal results for the ten tested city locations are for the most part used as a baseline to measure ice capacity factor effectiveness in the tested climate zone location. From here, these non-optimal results are judge and analyzed in determining the ranges of input variables to use for the genetic algorithm that produced the optimal results moving forward. The non-optimal design generally focused on the trial and error approach in seeking results to be reviewed in advancing the research onward and reaching an optimal design. The results indicated the direction in which the optimal results would be reached as well as, which ice capacity factors were more consistent, based on location and climate zone.

4.4 Test Location Optimal Results

4.4.1 How it works. The final part of the research involved the use of the genetic algorithm optimization tool. The results gathered during the previous research is used to help determine the variables that will be input and allow the optimization tool to define the best results for energy cost savings for the ice thermal storage technology. The manual results found in the prior work was simply a product of trial and error and was key in finding a primary direction in which to investigate further to find optimal results. After analyzing those results the variables pointing to the closest of minimum energy cost and energy consumption was extracted and set as the range for the input variables when prompted using the genetic algorithm optimization tool. From here the genetic algorithm optimization tool runs the program seeking a clear and concise result for the optimal energy cost savings. When this is completed the actual input variables that brought about that optimal energy cost savings are also displayed; then they ultimately are considered the ice thermal storage technology's design parameters for optimal energy cost savings.

4.4.2 The ten test locations optimal results. After having run tests and simulations for ten locations across the United States, the most optimal results have been compiled for the design and use of ice thermal storage technology in these cities. The cities consisted of locations comprised of seven ASHRAE climate zones and spanned the moist, dry, and marine climate subtypes. Testing was designed and performed on a trial and error basis to test many possibilities of ice thermal storage design based on factors for: ice capacity factor, ice charge time, ice discharge time, and the chiller size factor. All possibilities and trials were compared upon the output for energy consumption, as well as the more important energy cost. The optimal results were gathered for each city and combined together in a table. A complete comparison for all ten tested cities can be viewed in Table 11 below.

Table 11

Optimization results for ITS designs from genetic algorithm simulations.

Location	Miami	Orlando	Dallas	Greensboro	Philadelphia	Green Bay	Portland	Phoenix	San Diego	Seattle
Inputs										
Ice Capacity Factor	8	8	12	12	9	10	10	10	9	10
Ice Charge Time	0	0	0	1	0	0	2	0	1	3
Ice Discharge Time	12	12	12	12	12	12	12	12	12	12
Chiller Size Factor	1	0.95	0.85	0.8	0.85	0.85	0.85	0.85	0.85	0.85
Outputs										
Energy Cost ($)	16933	14834	11593	8035	6775	4275	3810	11269	6255	2360
Energy Consumption (kWh)	296030	259340	202680	140460	118450	74732	66614	197000	109370	39600

The data shown in the table above for the optimization results in ice thermal storage design display the differences in the ice thermal storage design from city and climate location. The results from location to location show a decrease in energy consumption and cost as the locations move further north and the climate zone number rises. It is very apparent that colder climates will result in lesser savings with the use of ice thermal storage. This is primarily due to colder climates requiring a substantially less amount of cooling than southern, hotter climates. The results indicate that the higher ice capacity factors were better for colder climates; as well as a lower chiller size factor in colder climates. It was also evident that the much colder climates required later ice charge times, which was primarily due to less required cooling. The optimal results found differ from the manual, trial and error results, in the aspect that they are a lot more refined and hone in on the utmost savings in the new ITS technology.

4.5 Energy consumption

The focus of this study and research was designed and concerned primarily for the energy costs that resulted from the cooling load required of commercial type buildings. As the work progressed, it also became just as important to make an emphasis to monitor the output results this new ice thermal storage technology makes on the building's energy consumption. Although the implementation of ice thermal storage results in a savings on energy costs for commercial buildings, ice thermal storage ultimately increases the amount of energy consumption that is caused by the building. This increase in energy consumption however is only a minor concern because of the savings, that is in full responsibility due to the decline in energy costs from the ITS system. Increases in the amount of energy consumed by the building with the addition of ice thermal energy is most easily explained and accounted for by the operation of the chiller. With the employment of ITS the chiller runs at night. When the chiller has to run at night to make the ice for the ITS tanks it is required to run at a higher capacity to be cold enough, making ice. The energy consumption increase is due to the extent of how much harder the chiller works and runs while making ice. With the correct design and optimization of ITS input variables, energy consumption became another output result monitored and focused on in minimizing. The results are shown below in Figure 15 for the optimal results in each city that was tested along with the corresponding energy consumption output results for that test location.

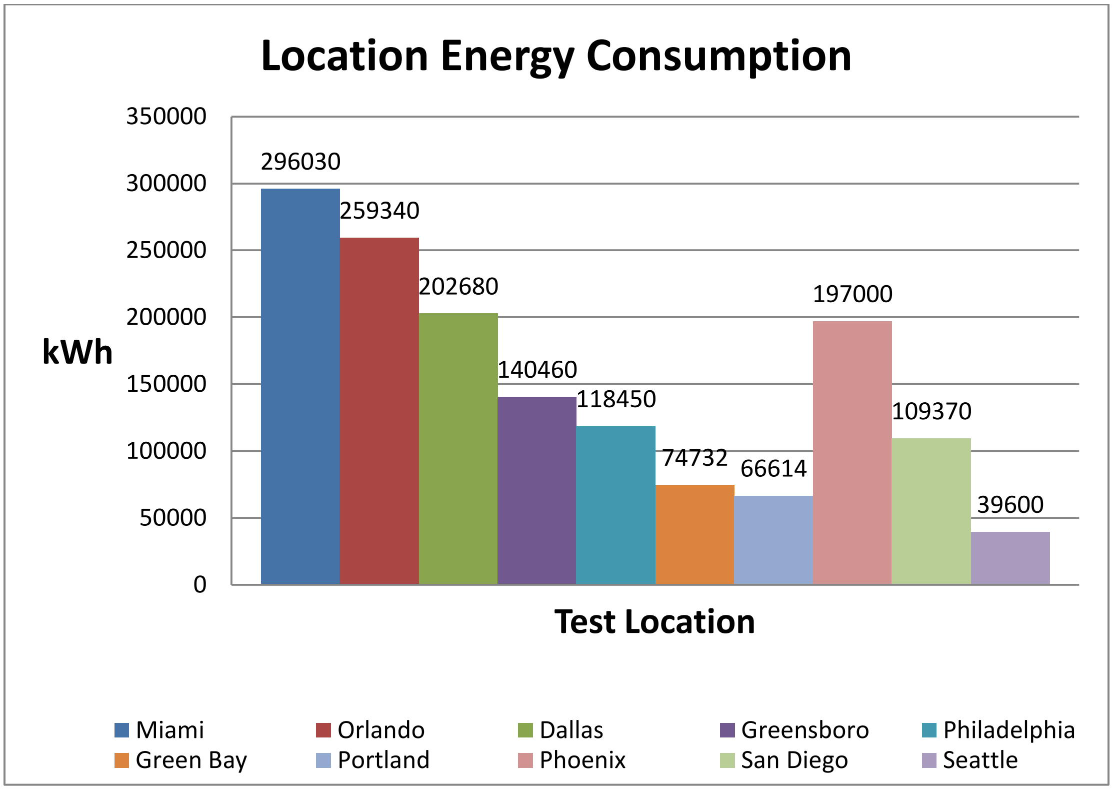

Figure 15 The optimal results for energy consumption in the ASHRAE climate zone test locations.

The optimal results shown here in Figure 15 represent the ice thermal storage and total cooling system's energy consumption in a year's time for the test locations. The energy consumption outputs, in each respective test location, varied; and were later determined to be due to climate zone needs for cooling. The climate zones of colder regions tended to produce less energy consumption from cooling, while the warmer climates accounted for a substantial amount of cooling. The graph in the Figure 15 above shows the relationship between the location and the energy consumption as the weather becomes colder.

4.6 Energy Cost

Overall the most important aspect of the results was surrounded by the energy costs discoveries. Efforts are now widespread in making buildings as energy efficient as possible and eliminating some of the energy costs that are a product of the cooling loads from commercial buildings. It was first priority to reduce the energy costs for cooling within the IRC test building that was simulated in the ten test locations throughout the United States. The results are shown below in Figure 16 for the optimal results in each city that was tested along with the corresponding energy costs output results for that test location. The graph in the figure below shows the relationship between the location and the energy costs as the climates turned colder. Optimal results shown in the figure below are represented for the total cooling costs for the year within the air conditioning system, including the ice thermal storage unit. Data is shown for all test locations spread across climate zones and climate subtypes recognized by ASHRAE. Analysis of these results was very much similar and fall in line with the theme that was found present for the energy consumption data results. Hotter climates definitely saw the most potential savings for energy costs in oppose to the colder climate zone cities tested. This is very much due to the aforementioned reasons of there being a lack of demand for cooling in primarily cold weather climates. The interesting aspect that turns out in the energy costs results reside in the amount of potential savings in relation to the negative increase of potential energy consumption. The ratio of decreasing energy costs to the increasing energy consumption is highly favorable towards the energy costs. This is very much desired and respected for a positive feedback in the value and efficiency of ice thermal storage usage.

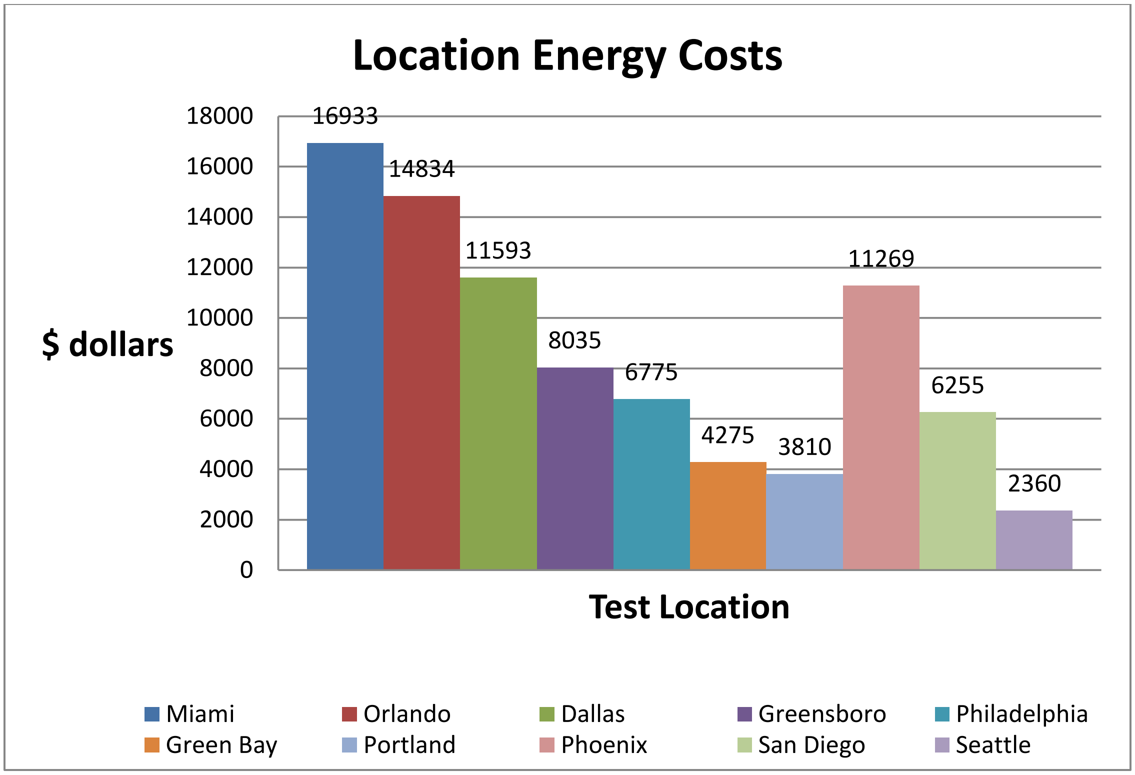

Figure 16 The optimal results for energy costs in the ASHRAE climate zone test locations.

CHAPTER 5

Conclusion and Future Research

5.1 Overview

The testing of ice thermal storage technology in various ASHRAE climate zones has presented a great deal of positivity on the idea of the technology being a source of energy cost savings. The outcome of results illustrates the immense effect the input variables made on energy cost and energy consumption as it pertains to cooling. The input variables that affect these two outcomes are both variables that can be controlled, as well as ones that there are not any control over. The controlled variables included; ice capacity factor, ice charge time, ice discharge time, chiller size factor, and variable ranges for the genetic algorithm optimization tool. The uncontrolled variables were; location climate and weather data, as well as the utility cost rate structure. The effects the input variables had on outcomes for energy cost and consumption was directly proportional to each other; when one affected cost it even affected consumption as well. The savings and outcome of this study is a useful tool in conveying the perks and advantages of ice thermal storage as an energy cost saver, but more research is essential in improving the advancement of the technology. Some key ways to further improve the research of this technology include; performing a cost analysis for the implementation of ice thermal storage into current commercial buildings, and even expanding the optimization genetic algorithm to handle more instances and different cases throughout the simulations of the year. All in all, the savings found in these simulated tests provide evidence that the application of ice thermal storage can provide energy cost savings, although differently depending upon a location's climate.

5.2 Input Variables

5.2.1 Ice capacity factor. This is the most important input variable throughout the research, as it is key to the cooling of the building during the stretch of the on-peak time period. The ice capacity factor is the variable that is assigned to determine the amount of time it will take for the ITS system to charge ice up to full capacity. It is most important that the ice capacity factor for the ice thermal storage be designed to adequately cover the cooling load during the on-peak period of the day where charges are much higher than the normal off-peak periods. In addition to that key factor, it is just as equally important that the ice capacity factor isn't oversized, as oversizing the ice capacity factor will take away from potential energy cost savings that would result from this technology. It was determined that the initial test run manually in the program would be for ice capacity factors ranging from a four all the way up to twelve. This was tested in all locations and from here interpretations were made in deciding parameters for the genetic algorithm optimization tool. Throughout the results it is indicated that ice capacity factors were most dependable in the mid to high ranges, but varied by climate location.

5.2.2 Ice charge time. The next of the input variables consisted of the settings that start the charging process for the ice thermal storage system. In addition to making sure there is enough capacity of cooling to complete the cooling load required during the on-peak period, it is also necessary to start the charging of the ice in time to ensure that the ice capacity is met before the building becomes operational at the beginning of the day and the chiller is running to meet the normal daytime cooling portion for the off-peak time. The ice charge time variable handles this process and assigns the time in which to start this charging process of ice for the system. For the manual test here the trials consisted of four separate ice charge time to start the charging period; they included: 11pm, 12am midnight, 1am, and 2am. The charging period for the ice was designed to occur at night. This was due to multiple reasons which include it be during an off-peak time period, for obvious reasons of energy cost savings, and also during a time period where the chiller is not being run by the system for cooling of the building, leaving the only available time to be when the building is not considered to be operational. The ice charge strategy times were run for each of the ice capacity factors that ranged from four to twelve and ultimately considered in the deciding parameters for the genetic algorithm.

5.2.3 Ice discharge time. The ice discharge time was the easiest of the input variables due to the fact that it remained constant and also because of the fact it is dependent upon another uncontrolled variable. The ice discharge time is reliant upon the factor known as the utility cost rate structure. The utility cost rate structure sets the on-peak and off-peak time periods and in addition to this, the utility cost rate structure states the charges for both of these time periods. This links the ice discharge time to the utility rate structure by the setting of the on-peak time period. The cooling for the building during the on-peak time period needs to be controlled by the ice thermal storage system, therefore, the ice discharge time must be set to begin at the moment the on-peak time period is set to being each day. For this reason the ice discharge time remains constant all throughout the manual testing, as well as the genetic algorithm optimization process also. In future works any changes to the utility cost rate structure where it would alter the on-peak time period, it would mean the ice discharge time should likewise be reset to match the on-peak start time.

5.2.4 Chiller size factor. The chiller size factor for the experiment is another input variable that saw little change initially; but unlike the ice discharge time, the chiller size factor was later altered and tested for efficiency. The purpose of the chiller size factor is solely to determine how much to oversize the chiller. For purposes of this research, the chiller size factor being used to oversize the chiller also is the standard which is used to oversize the storage capacity of the ice, due to the fact that ice capacity is determined based off of chiller size. In the most common of cases it is necessary to allow for an appropriate safety factor of 20% of the chiller size, resulting in a chiller size factor of 1.2. This was the case that was run in the manual testing for the initial baseline trial and error data. For each run tested a chiller size factor of 1.2 was set and this consequently oversized the chiller as well as the capacity of ice storage by 20%. During the optimizing of the ITS design using the genetic algorithm is when the chiller size factor variable saw changes to its otherwise constant and consistent setting of 1.2. Here during this optimizing period the range for this variable was spanned anywhere from possibly being oversized or even undersized by 20%. The chiller size factor was given the option of outputting a result anywhere from 0.8 to 1.2. This was determined to be feasible because of the chiller being designed for the worst possible case of cooling load desired and the use of the ITS system resulting in downsizing the likelihood of that worst possible case actually happening or coming true.

5.3 Savings

Studying the optimization of ice thermal storage technology throughout the ASHRAE climate zones has given rise to a viable source for energy cost savings. Looking over the results and analyzing the data from all ten test locations, which were spread throughout seven climate zones and three climate subtypes, many conclusions can be drawn regarding the promising possibilities that the implementation of ice thermal storage technology presents in incorporating into the cooling processes of commercial buildings. The outputs for the optimal results of energy consumption and energy costs can be seen in Table 12 below for both a system with no ice thermal storage as well as an optimized ice thermal storage system. These results are shown for all ten test locations in a combined table for all of the climate zone test locations. Finally the key takeaway from this table resides in the row labeled for the percent savings. Here, the percent savings is calculated to show just how much savings was established in energy costs, comparing the results between the system run with no ITS technology and with the implementation of an optimized ITS system. There also is two graphics shown below in Figure 17 and Figure 18 that display these results of the differences in the IRC building run with and without the application of an ITS system based on energy consumption and energy costs respectively.

Table 12

Outputs for energy cost & consumption for No ITS vs. Optimal ITS & percent savings.

Location	**Miami**		**Orlando**		**Dallas**		**Greensboro**		**Philadelphia**	
System	No ITS	Optimal	No ITS	Optimal	No ITS	Optimal	No ITS	Optimal	No ITS	Optimal
Outputs										
Energy Cost ($)	27420	16933	24790	14834	21850	11593	17070	8035	15080	6775
Energy Consumption (kWh)	255150	296030	227430	259340	181980	202680	126950	140460	106150	118450
Percent Savings (%)	38.2		40.2		46.9		52.9		55.1	
Location	**Green Bay**		**Portland**		**Phoenix**		**San Diego**		**Seattle**	
System	No ITS	Optimal	No ITS	Optimal	No ITS	Optimal	No ITS	Optimal	No ITS	Optimal
Outputs										
Energy Cost ($)	12205	4275	10337	3810	20610	11269	13169	6255	8395	2360
Energy Consumption (kWh)	69761	74732	61499	66614	179700	197000	94116	109370	34808	39600
Percent Savings (%)	65.0		63.1		45.3		52.5		71.9	

One key takeaway from the studies lies within the changes observed by the results produced within the genetic algorithm optimization tool used in seeking the best design results for input variables. These changes were present throughout the different climate zones as it pertains to the ice capacity factor and chiller size factor input variables. The ice capacity factor that worked for optimal cases in the ten locations that were tested changed and seemed to be based upon the climate of the location. In the warm and hotter climate zones the consistently optimal return for ice capacity factor exhibited to be in the midrange of the data parameters tested. However, when it came to the findings for colder climates, the ice capacity factor results saw a steady increase. Cold weather locations saw optimal design results always at the far end of the spectrum near the higher tested ice capacity factors. Moving on, the chiller size factor displayed some of the same effects. For the higher climate zones, which represent the colder climates, the chiller size factor was able to be designed for an under-sizing rather than the typical oversizing, which is done to allow a safety factor load. In the warmer climate regions these locations provided chiller size factor results that steered closer to the actual size of the design chiller, allowing for neither an oversizing nor a substantial under-sizing. These changes within the design input variables were the initial findings that pointed towards the climate zones having a more than substantial effect on the produced results. The most noticeable of these deductions include the differences of the produced results in comparison to the tested climate zones. This major giveaway that ultimately proved truth to the climate's effect on the results lied within results themselves. As the research developed it became easily apparent the relationship the climate location has on the savings potential. Colder climates require far less energy for cooling and therefore provide far less results in the amount of savings possibilities. As the locations were tested in northern and cold weather climate, the results dropped off aggressively and the energy consumption along with the energy costs seemed minimal to none, in comparison to the warmer, hot weather climates. Colder climates see a bigger portion of their energy consumption in heating costs and ice thermal storage cannot target that to provide any energy cost savings. It proved that savings from on energy costs can range depending upon locations, but were as low an 38% savings in one location, and as high as an 72% savings in another location. Although these findings prove to show differences in the amount of results in energy savings by climate zone, still savings with this technology can exist in every type of climate, cold or hot. All in all, there is a prominent energy savings capability with the correct optimization of ice thermal storage technology when designed accordingly, regardless of the climate zone. Ice thermal storage technology can play a key role in the reduction of energy cost in the cooling of commercial buildings.

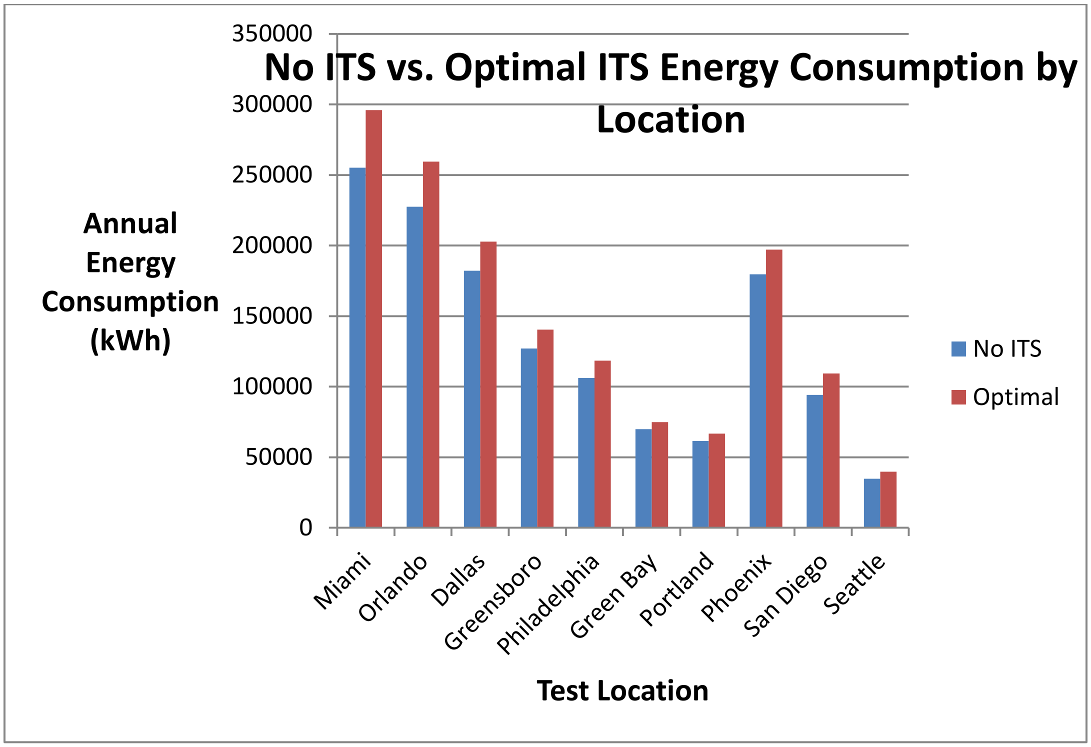

Figure 17 Graph comparing energy consumption of No ITS system vs. optimized ITS system.

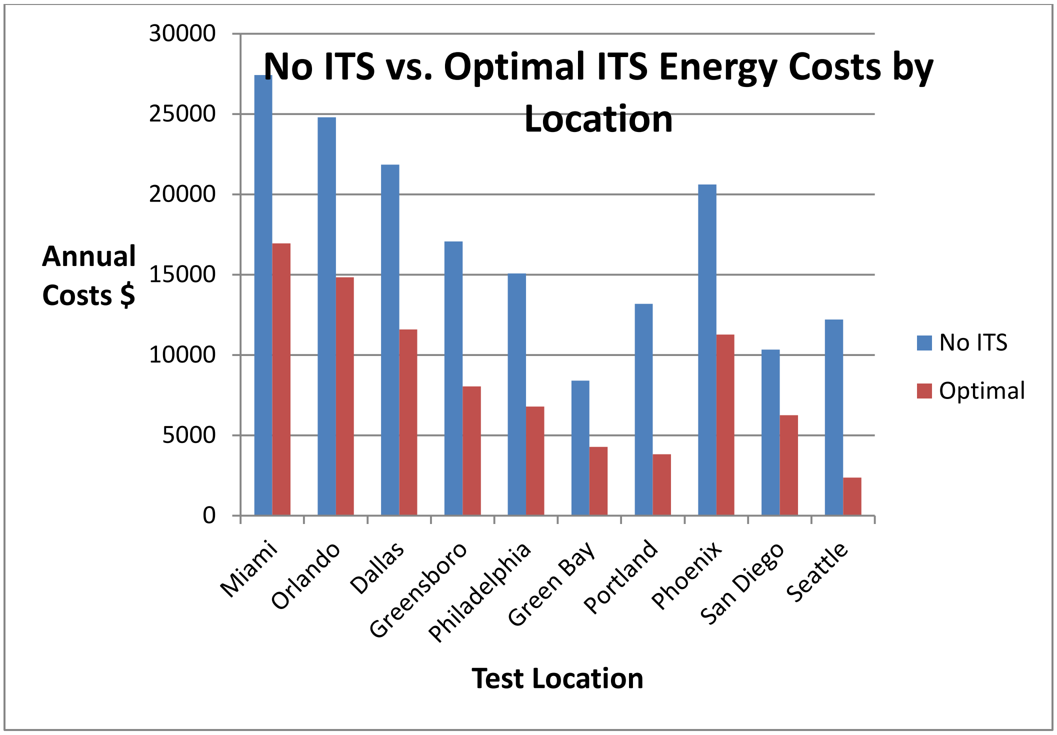

Figure 18 Graph comparing energy cost of No ITS system vs. optimized ITS system.

5.4 Moving Forward

Just like with any great discovery, there is never room for complacency or a need to consider it finished; there is always room for some sort of improvement. This long for further enhancement is what has made some of the great technological advancements in the world today very much possible. This belief is also very much true as it pertains to ice thermal storage technology. In the future this technology can be advanced with some points of interest to be looked deeper into and investigated. The most important and substantial of these forms of progression include performing a cost analysis for ice thermal storage technology, along with any improvements of the current programs that run and simulate these tests used to find the outcome results of data.

5.4.1 Cost Analysis. It is no surprise the practicality of ice thermal storage technology in energy cost savings. The implementation of this technology into the real world today is already present and exists in both primarily cold and hot climates. The need for completing a cost analysis on the technology would be to further explore the overall benefit in just how cost effective it is to implement while being sure it remains beneficial and worth-while in the long-term. This particular study would include and consist of a research of initial costs, and operational costs. Often it is a cause for concern in dealing with these types of expenses where it can even outweigh long-term savings down the road. Another portion of the study would examine a plan for the return of investment. This is generally a performance measure where the efficiency of an investment is evaluated. Here the investments, including initial costs, operational costs, and any upkeep or maintenance are used to equate just how profitable the investment was based on making up expenses and calculating possible future income or savings.

5.4.2 Program and code improvements. The perfecting of the already developed codes and programs used in this research is another extraordinary way to continue to advance the work already discovered here for ice thermal storage technology and design. The ice thermal storage optimization program has room for growth by expanding the optimization genetic algorithm to handle more instances and different cases throughout the simulations of the year. Such advances in the optimization algorithm can embrace aspects including using more tested ice charge times, and many other alterations in code design. Another major way of changing the testing would be to explore the possibility of using a longer charging time period. It is also worth looking into the possible savings that could be achieved if the ice thermal storage system replaced and took control of all cooling while the building is operational, including on-peak periods as well as off-peak periods. This possibility would mean for a lot more ice charging and therefore need tons more of ice capacity. This would more than likely result in a constantly charging period for the ice capacity with the exception of the on-peak time period. These types of future advances and/or upgrades to the ice thermal storage optimization program will advance the technology and make for a well-balanced and investigated energy cost saving tool for commercial buildings' cooling.

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Appendix A

A. Hourly Peak Load Data

Table A1

Hourly peak load data for the design day in Miami, Florida.

Peak Load Day:	July 29th				
Month	Day	Hour	Building cool load (coils+losses&gains) (Btu/hr)	Outside wet-bulb temp (F)	Outside dry-bulb temp (F)
7	29	1	0	76	79
7	29	2	0	76	78
7	29	3	0	76	78
7	29	4	0	76	79
7	29	5	0	76	78
7	29	6	0	76	79
7	29	7	2.13E+06	77	81
7	29	8	2.85E+06	78	84
7	29	9	2.79E+06	79	84
7	29	10	2.65E+06	77	84
7	29	11	2.74E+06	79	85
7	29	12	2.79E+06	80	85
7	29	13	2.60E+06	78	86
7	29	14	2.70E+06	80	87
7	29	15	2.64E+06	79	87
7	29	16	2.60E+06	78	86
7	29	17	1.47E+06	78	86
7	29	18	0	77	85
7	29	19	0	77	84
7	29	20	0	77	83
7	29	21	0	77	82
7	29	22	0	76	82
7	29	23	0	76	82
7	29	24	0	77	81

Table A2

Hourly peak load data for the design day in Orlando, Florida.

Peak Load Day:	July 8th				
Month	Day	Hour	Building cool load (coils+losses&gains) (Btu/hr)	Outside wet-bulb temp (F)	Outside dry-bulb temp (F)
7	8	1	0	75	78
7	8	2	0	74	77
7	8	3	0	74	76
7	8	4	0	74	75
7	8	5	0	73	74
7	8	6	0	73	74
7	8	7	2.01E+06	75	77
7	8	8	2.76E+06	76	80
7	8	9	2.66E+06	76	84
7	8	10	2.65E+06	76	87
7	8	11	2.62E+06	76	89
7	8	12	2.56E+06	76	91
7	8	13	2.40E+06	74	92
7	8	14	2.29E+06	72	94
7	8	15	2.30E+06	72	94
7	8	16	2.51E+06	75	96
7	8	17	1.31E+06	75	95
7	8	18	0	76	87
7	8	19	0	75	82
7	8	20	0	74	80
7	8	21	0	75	80
7	8	22	0	75	79
7	8	23	0	75	78
7	8	24	0	75	78

Table A3

Hourly peak load data for the design day in Dallas, Texas.

Peak Load Day:	July 15th				
Month	Day	Hour	Building cool load (coils+losses&gains) (Btu/hr)	Outside wet-bulb temp (F)	Outside dry-bulb temp (F)
7	15	1	0	71	80
7	15	2	0	72	80
7	15	3	0	72	79
7	15	4	0	71	77
7	15	5	0	71	77
7	15	6	0	71	76
7	15	7	2.34E+06	73	79
7	15	8	2.86E+06	74	82
7	15	9	2.74E+06	74	86
7	15	10	2.82E+06	76	90
7	15	11	2.78E+06	76	92
7	15	12	2.71E+06	76	95
7	15	13	2.61E+06	75	95
7	15	14	2.63E+06	76	97
7	15	15	2.53E+06	74	96
7	15	16	2.42E+06	73	89
7	15	17	1.29E+06	73	87
7	15	18	0	72	89
7	15	19	0	73	89
7	15	20	0	73	86
7	15	21	0	72	83
7	15	22	0	71	81
7	15	23	0	70	80
7	15	24	0	70	79

Table A4

Hourly peak load data for the design day in Greensboro, North Carolina.

Peak Load Day:	July 8th				
Month	Day	Hour	Building cool load (coils+losses&gains) (Btu/hr)	Outside wet-bulb temp (F)	Outside dry-bulb temp (F)
7	8	1	0	69	70
7	8	2	0	69	70
7	8	3	0	68	69
7	8	4	0	68	68
7	8	5	0	67	68
7	8	6	0	68	69
7	8	7	1.24E+06	70	73
7	8	8	2.53E+06	74	78
7	8	9	2.48E+06	75	82
7	8	10	2.45E+06	75	83
7	8	11	2.45E+06	75	84
7	8	12	2.42E+06	75	85
7	8	13	2.46E+06	76	87
7	8	14	2.36E+06	75	82
7	8	15	2.42E+06	76	86
7	8	16	2.44E+06	76	87
7	8	17	1.36E+06	75	85
7	8	18	0	76	84
7	8	19	0	76	84
7	8	20	0	75	79
7	8	21	0	74	78
7	8	22	0	74	75
7	8	23	0	73	74
7	8	24	0	73	74

Appendix B

B. Full Data For Each Climate Zone

Table B1

Full data results for climate zone 1 in Miami, Florida.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		22927	301,200
4	0	12	1.2		22133	298650
4	1	12	1.2		22133	298650
4	2	12	1.2		21943	298070
5	23	12	1.2		17257	301700
5	0	12	1.2		17096	29888
5	1	12	1.2		17096	29888
5	2	12	1.2		17611	298330
6	23	12	1.2		17268	301890
6	0	12	1.2		17120	299310
6	1	12	1.2		17120	299310
6	2	12	1.2		17085	298690
7	23	12	1.2		17281	302120
7	0	12	1.2		17134	299550
7	1	12	1.2		17134	299550
7	2	12	1.2		17096	298870
8	23	12	1.2		17296	302380
8	0	12	1.2		17147	299780
8	1	12	1.2		17147	299780
8	2	12	1.2		17111	299140
9	23	12	1.2		17310	302610
9	0	12	1.2		17160	300000
9	1	12	1.2		17160	300000
9	2	12	1.2		17123	299350
10	23	12	1.2		17340	303140
10	0	12	1.2		17178	300310
10	1	12	1.2		17178	300310
10	2	12	1.2		17142	299680
11	23	12	1.2		17350	303330
11	0	12	1.2		17188	300490
11	1	12	1.2		17188	300490
11	2	12	1.2		17168	300140
12	23	12	1.2		17364	303560
12	0	12	1.2		17212	300910
12	1	12	1.2		17212	300910
12	2	12	1.2		17178	300320

Table B2

Full data results for climate zone 2 in Orlando, Florida.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		17395	264,800
4	0	12	1.2		18239	262280
4	1	12	1.2		18239	262280
4	2	12	1.2		17965	261970
5	23	12	1.2		15168	265170
5	0	12	1.2		15007	262360
5	1	12	1.2		15007	262360
5	2	12	1.2		15329	262210
6	23	12	1.2		15177	265330
6	0	12	1.2		15037	262890
6	1	12	1.2		15037	262890
6	2	12	1.2		15006	262340
7	23	12	1.2		15187	265520
7	0	12	1.2		15043	262990
7	1	12	1.2		15043	262990
7	2	12	1.2		15017	262530
8	23	12	1.2		15199	265720
8	0	12	1.2		15054	263180
8	1	12	1.2		15054	263180
8	2	12	1.2		15026	262700
9	23	12	1.2		15211	265920
9	0	12	1.2		15061	263310
9	1	12	1.2		15061	263310
9	2	12	1.2		15041	262950
10	23	12	1.2		15233	266310
10	0	12	1.2		15070	263470
10	1	12	1.2		15070	263470
10	2	12	1.2		15051	263130
11	23	12	1.2		15228	266220
11	0	12	1.2		15081	263660
11	1	12	1.2		15081	263660
11	2	12	1.2		15061	263330
12	23	12	1.2		15237	266380
12	0	12	1.2		15097	263930
12	1	12	1.2		15097	263930
12	2	12	1.2		15070	263460

Table B3

Full data results for climate zone 3 in Dallas, Texas.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		16250	209,360
4	0	12	1.2		16083	205800
4	1	12	1.2		16083	205800
4	2	12	1.2		15592	205130
5	23	12	1.2		12000	209800
5	0	12	1.2		11790	206120
5	1	12	1.2		11790	206120
5	2	12	1.2		11751	205430
6	23	12	1.2		12012	209990
6	0	12	1.2		11800	206290
6	1	12	1.2		11800	206290
6	2	12	1.2		11761	205610
7	23	12	1.2		12021	210160
7	0	12	1.2		11809	206460
7	1	12	1.2		11809	206460
7	2	12	1.2		11770	205780
8	23	12	1.2		12031	210330
8	0	12	1.2		11819	206620
8	1	12	1.2		11819	206620
8	2	12	1.2		11780	205940
9	23	12	1.2		12040	210490
9	0	12	1.2		11828	206790
9	1	12	1.2		11828	206790
9	2	12	1.2		11790	206110
10	23	12	1.2		12049	210660
10	0	12	1.2		11840	206990
10	1	12	1.2		11840	206990
10	2	12	1.2		11802	206320
11	23	12	1.2		12059	210820
11	0	12	1.2		11848	207140
11	1	12	1.2		11848	207140
11	2	12	1.2		11810	206470
12	23	12	1.2		12066	210940
12	0	12	1.2		11856	207280
12	1	12	1.2		11856	207280
12	2	12	1.2		11821	206660

Table B4

Full data results for climate zone 4 in Greensboro, North Carolina.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		12566	145,950
4	0	12	1.2		12310	143040
4	1	12	1.2		12310	143040
4	2	12	1.2		12303	142210
5	23	12	1.2		8366	146260
5	0	12	1.2		8183	143060
5	1	12	1.2		8183	143060
5	2	12	1.2		10017	142310
6	23	12	1.2		8374	146400
6	0	12	1.2		8193	143230
6	1	12	1.2		8193	143230
6	2	12	1.2		8154	142550
7	23	12	1.2		8384	146570
7	0	12	1.2		8201	143370
7	1	12	1.2		8201	143370
7	2	12	1.2		8156	142590
8	23	12	1.2		8392	146710
8	0	12	1.2		8207	143470
8	1	12	1.2		8207	143470
8	2	12	1.2		8165	142740
9	23	12	1.2		8402	146880
9	0	12	1.2		8217	143660
9	1	12	1.2		8217	143660
9	2	12	1.2		8174	142900
10	23	12	1.2		8418	147160
10	0	12	1.2		8225	143800
10	1	12	1.2		8225	143800
10	2	12	1.2		8185	143090
11	23	12	1.2		8417	147150
11	0	12	1.2		8233	143940
11	1	12	1.2		8233	143940
11	2	12	1.2		8195	143260
12	23	12	1.2		8417	147150
12	0	12	1.2		8238	144020
12	1	12	1.2		8238	144020
12	2	12	1.2		8205	143420

Table B5

Full data results for climate zone 5 in Philadelphia, Pennsylvania.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		8933	121,870
4	0	12	1.2		9027	119970
4	1	12	1.2		9027	119970
4	2	12	1.2		8885	119650
5	23	12	1.2		6993	122260
5	0	12	1.2		6874	120170
5	1	12	1.2		6874	120170
5	2	12	1.2		7147	119770
6	23	12	1.2		7003	122430
6	0	12	1.2		6879	120260
6	1	12	1.2		6879	120260
6	2	12	1.2		6865	120010
7	23	12	1.2		7012	122580
7	0	12	1.2		6883	120320
7	1	12	1.2		6883	120320
7	2	12	1.2		6853	119810
8	23	12	1.2		7021	122750
8	0	12	1.2		6891	120470
8	1	12	1.2		6891	120470
8	2	12	1.2		6862	119960
9	23	12	1.2		7030	122910
9	0	12	1.2		6901	120650
9	1	12	1.2		6901	120650
9	2	12	1.2		6871	120120
10	23	12	1.2		7040	123070
10	0	12	1.2		6912	120840
10	1	12	1.2		6912	120840
10	2	12	1.2		6880	120280
11	23	12	1.2		7049	123230
11	0	12	1.2		6920	120970
11	1	12	1.2		6920	120970
11	2	12	1.2		6889	120440
12	23	12	1.2		7058	123380
12	0	12	1.2		6929	121130
12	1	12	1.2		6929	121130
12	2	12	1.2		6899	120600

Table B6

Full data results for climate zone 6 in Green Bay, Wisconsin.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		6400	77,214
4	0	12	1.2		6029	75424
4	1	12	1.2		6029	75424
4	2	12	1.2		5746	74935
5	23	12	1.2		4428	77415
5	0	12	1.2		4319	75499
5	1	12	1.2		4319	75499
5	2	12	1.2		5020	74996
6	23	12	1.2		4433	77495
6	0	12	1.2		4328	75655
6	1	12	1.2		4328	75655
6	2	12	1.2		4308	75311
7	23	12	1.2		4440	77629
7	0	12	1.2		4336	75806
7	1	12	1.2		4336	75806
7	2	12	1.2		4311	75372
8	23	12	1.2		4449	77784
8	0	12	1.2		4329	75677
8	1	12	1.2		4329	75677
8	2	12	1.2		4316	75446
9	23	12	1.2		4456	77899
9	0	12	1.2		4336	75803
9	1	12	1.2		4336	75803
9	2	12	1.2		4307	75299
10	23	12	1.2		4460	77969
10	0	12	1.2		4339	75857
10	1	12	1.2		4339	75857
10	2	12	1.2		4315	75432
11	23	12	1.2		4464	78046
11	0	12	1.2		4348	76006
11	1	12	1.2		4348	76006
11	2	12	1.2		4324	75586
12	23	12	1.2		4455	77889
12	0	12	1.2		4353	76095
12	1	12	1.2		4353	76095
12	2	12	1.2		4332	75740

Table B7

Full data results for climate zone 7 in Portland, Maine.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		4184	68,713
4	0	12	1.2		4670	67392
4	1	12	1.2		4670	67392
4	2	12	1.2		4854	66904
5	23	12	1.2		3947	68994
5	0	12	1.2		3861	67506
5	1	12	1.2		3861	67506
5	2	12	1.2		3837	67076
6	23	12	1.2		3944	68949
6	0	12	1.2		3873	67702
6	1	12	1.2		3873	67702
6	2	12	1.2		3846	67229
7	23	12	1.2		3952	69090
7	0	12	1.2		3881	67842
7	1	12	1.2		3881	67842
7	2	12	1.2		3853	67365
8	23	12	1.2		3960	69233
8	0	12	1.2		3888	67979
8	1	12	1.2		3888	67979
8	2	12	1.2		3860	67476
9	23	12	1.2		3968	69371
9	0	12	1.2		3896	68105
9	1	12	1.2		3896	68105
9	2	12	1.2		3868	67617
10	23	12	1.2		3976	69502
10	0	12	1.2		3901	68204
10	1	12	1.2		3901	68204
10	2	12	1.2		3876	67763
11	23	12	1.2		3983	69632
11	0	12	1.2		3908	68327
11	1	12	1.2		3908	68327
11	2	12	1.2		3884	67898
12	23	12	1.2		3997	69871
12	0	12	1.2		3916	68468
12	1	12	1.2		3916	68468
12	2	12	1.2		3890	68009

Table B8

Full data results for climate zone 2 in Phoenix, Arizona.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		13783	204,130
4	0	12	1.2		13553	199040
4	1	12	1.2		13553	199040
4	2	12	1.2		13283	197890
5	23	12	1.2		11685	204280
5	0	12	1.2		11402	199330
5	1	12	1.2		11402	199330
5	2	12	1.2		11331	198090
6	23	12	1.2		11694	204450
6	0	12	1.2		11411	199490
6	1	12	1.2		11411	199490
6	2	12	1.2		11340	198250
7	23	12	1.2		11704	204620
7	0	12	1.2		11422	199690
7	1	12	1.2		11422	199690
7	2	12	1.2		11350	198420
8	23	12	1.2		11714	204790
8	0	12	1.2		11432	199860
8	1	12	1.2		11432	199860
8	2	12	1.2		11359	198590
9	23	12	1.2		11723	204950
9	0	12	1.2		11439	200000
9	1	12	1.2		11439	200000
9	2	12	1.2		11369	198760
10	23	12	1.2		11731	205090
10	0	12	1.2		11448	200140
10	1	12	1.2		11448	200140
10	2	12	1.2		11378	198920
11	23	12	1.2		11741	205260
11	0	12	1.2		11453	200230
11	1	12	1.2		11453	200230
11	2	12	1.2		11388	199090
12	23	12	1.2		11749	205400
12	0	12	1.2		11462	200390
12	1	12	1.2		11462	200390
12	2	12	1.2		11396	199230

Table B9

Full data results for climate zone 3 in San Diego, California.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		6320	110,480
4	0	12	1.2		6247	109220
4	1	12	1.2		6247	109220
4	2	12	1.2		6425	108940
5	23	12	1.2		6328	110630
5	0	12	1.2		6257	109390
5	1	12	1.2		6257	109390
5	2	12	1.2		6239	109080
6	23	12	1.2		6338	110790
6	0	12	1.2		6266	109550
6	1	12	1.2		6266	109550
6	2	12	1.2		6248	109230
7	23	12	1.2		6347	110960
7	0	12	1.2		6277	109740
7	1	12	1.2		6277	109740
7	2	12	1.2		6257	109390
8	23	12	1.2		6357	111130
8	0	12	1.2		6287	109920
8	1	12	1.2		6287	109920
8	2	12	1.2		6267	109560
9	23	12	1.2		6365	111270
9	0	12	1.2		6296	110070
9	1	12	1.2		6296	110070
9	2	12	1.2		6274	109680
10	23	12	1.2		6374	111440
10	0	12	1.2		6304	110220
10	1	12	1.2		6304	110220
10	2	12	1.2		6283	109840
11	23	12	1.2		6384	111600
11	0	12	1.2		6313	110360
11	1	12	1.2		6313	110360
11	2	12	1.2		6292	110000
12	23	12	1.2		6395	111800
12	0	12	1.2		6321	110510
12	1	12	1.2		6321	110510
12	2	12	1.2		6302	110180

Table B10

Full data results for climate zone 4 in Seattle, Washington.

Inputs	Inputs	Inputs	Inputs		Outputs	Outputs
Ice Capacity Factor	Ice Charge Time	Ice Discharge Time	Chiller Size Factor		Cost for Year ($)	Energy for Year (kWh)
4	23	12	1.2		2965	40,793
4	0	12	1.2		2317	39653
4	1	12	1.2		2317	39653
4	2	12	1.2		2741	39434
5	23	12	1.2		2341	40925
5	0	12	1.2		2274	39762
5	1	12	1.2		2274	39762
5	2	12	1.2		2267	39630
6	23	12	1.2		2348	41046
6	0	12	1.2		2281	39874
6	1	12	1.2		2281	39874
6	2	12	1.2		2272	39712
7	23	12	1.2		2354	41157
7	0	12	1.2		2287	39984
7	1	12	1.2		2287	39984
7	2	12	1.2		2278	39823
8	23	12	1.2		2361	41281
8	0	12	1.2		2293	40092
8	1	12	1.2		2293	40092
8	2	12	1.2		2285	39939
9	23	12	1.2		2367	41379
9	0	12	1.2		2300	40196
9	1	12	1.2		2300	40196
9	2	12	1.2		2291	40059
10	23	12	1.2		2373	41489
10	0	12	1.2		2306	40311
10	1	12	1.2		2306	40311
10	2	12	1.2		2298	40172
11	23	12	1.2		2380	41612
11	0	12	1.2		2313	40428
11	1	12	1.2		2313	40428
11	2	12	1.2		2305	40293
12	23	12	1.2		2387	41733
12	0	12	1.2		2319	40548
12	1	12	1.2		2319	40548
12	2	12	1.2		2311	40402