Impact of Ice Storage on Electrical Energy Consumption in Large and Medium-sized Office Buildings in Different Climate Zones

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Abstract

Cooling demand constitutes a large portion of total electrical demand for office buildings during peak hours. Deteriorating load factors, increased use of more inefficient and polluting peaking units are the aftermaths of growth in peak demand challenging energy system efficiency and grid reliability.

Ice storage technology can help shift this peak cooling demand to off-peak periods. Ice storage reduces or even eliminates chiller operation during peak periods. The objective of the research is to analyze the chiller energy consumption of conventional non-storage and ice storage cooling systems for large and medium-sized office buildings in diverse climate zones. The research also quantifies the peak energy savings as a result of ice storage systems.

To accomplish the thesis objectives the Demand Response Quick Assessment Tool (DRQAT) has been used to model and simulate large and medium-sized office buildings in diverse climate zones with non-storage and ice storage cooling systems. Demand Response Quick Assessment Tool (DRQAT) has been developed by LBNL's Demand Response Research Center. It is based on the most popular features and capabilities of EnergyPlus and is downloadable from [1]. The construction and weather files in DRQAT have been modified to incorporate construction standards and weather data for the cities representing the diverse climate zones. The ice storage system's operating and control strategies investigated include full storage and partial storage with storage priority and chiller priority.

Research findings indicate that chiller energy consumption for non-storage and ice storage systems depends highly on climatic conditions. The climate zones with hot summers as well as small day and night temperature variations show higher chiller energy consumption. The marine climate zone has the lowest chiller energy consumption. The cold/humid climate zone has higher chiller energy consumption than the cold/dry and very cold climate zones. The cold/dry and very cold climate zones have comparable chiller energy consumption. The research findings will help utilities and building owners to quantify the benefits of installing ice storage systems in office buildings located in different climate zones.

Dedicated to my Husband

Sanaullah Nihal

Acknowledgement

I pay my utmost gratitude to Allah for his grace and blessings.

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List of Acronyms

AEO	Annual Energy Outlook
AHU	Air Handling Unit
ARI	Air-Conditioning and Refrigeration Institute
BLAST	Building Load and System Thermodynamics
COP	Coefficient of Performance
DOE	Department of Energy
DRQAT	Demand Response Quick Assessment Tool
EIA	Energy Information Administration
IT	Information Technology
LBNL	Lawrence Berkeley National Laboratory
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
RH	Relative Humidity
TMY3	Typical Meteorological Year 3
VAV	Variable Air Volume
WWR	Window to Wall Ratio

1. INTRODUCTION

1.1. Background

Total electricity consumption in office buildings is dominated by cooling. Internal loads generated by building occupants, lighting and computers impose a constant cooling load over the entire year. During summers cooling requirement is further increased due to additional loads such as solar heat gain through windows, conduction and infiltration through building envelope and ventilation requirement to maintain indoor air quality. In hot and humid climate zones the cooling requirement goes up further due to high ambient temperatures and humidity. Also buildings in these climate zones are often not well insulated or adequately sealed.

During daytime due to high cooling demand, the total electricity demand increases and imposes several problems for power companies. The utility meets this peak demand through more expensive peaking units. New plants built to meet peak demand are operated at full capacity only during the short peak periods and remain idle most of the time. With growing economy the peak demand is constantly increasing. Deteriorating load factors, increased use of more inefficient and polluting peaking units are the aftermaths of growth in peak demand challenging energy system efficiency and grid reliability.

Recently, thermal energy storage has gained prodigious attention as it can potentially reduce peak demand. By shifting demand to off-peak periods thermal (cool) energy storage allows the vast generation resources to be utilized when they are mostly idle. This reduces the need for peaking plant investment and construction. The combination of more efficient base generation plants, lower transmission and distribution line losses and cooler night-time temperatures offers cheaper night-time generation, which can be used for thermal (cool) energy storage.

From the available thermal energy storage technologies, ice storage permanently shifts energy use from peak periods to off-peak night periods thereby slashing the peak electricity demand. This is achieved by charging ice storage - that is freezing water - by operating chillers at off-peak periods and discharging the ice storage by melting ice during peak periods to meet building cooling demand. This raises the possibility to reduce or even eliminate the chiller operation during peak periods. The nighttime electricity is increasingly made of renewable wind energy with zero emissions. Hence ice storage can also use this efficient electricity generation at nighttime thereby reducing carbon footprints [2] [3].

A thorough literature search has been conducted to identify the knowledge gaps in the area of ice storage systems. This thesis purports to investigate the chiller energy consumption for large and medium-sized office buildings with ice storage systems in diverse climate zones.

1.2. Research Objectives

The objective of this research is to analyze the chiller energy consumption of conventional non-storage and ice storage cooling systems, as well as quantifying peak energy savings as a result of ice storage systems. This research focuses on the operation of ice storage systems in large and medium-sized office buildings in diverse climate zones.

To accomplish the thesis objectives, large and medium-sized office buildings have been modeled in Demand Response Quick Assessment Tool (DRQAT) with non-storage and ice storage cooling systems in diverse climate zones including hot/humid, hot/dry, mild/humid, marine, cold/humid, cold/dry and very cold zones. Demand Response Quick Assessment Tool (DRQAT) is based on EnergyPlus and requires the user to enter basic building information to calculate the chiller energy consumption for the non-storage and the ice storage systems. The non-storage systems include hydronic cooling system for large-sized office buildings and air-cooled systems for medium-sized office buildings. Different operating and control strategies of ice storage systems include full storage and partial storage with storage priority and chiller priority. The construction and weather files in Demand Response Quick Assessment Tool (DRQAT) have been modified to incorporate construction standards and weather data for the US cities representing the diverse climate zones.

1.3. Literature Search and Gap Analysis

Intensive research is going on in the field of thermal energy storage systems. Authors in [4] provide an extensive review of various types of thermal energy storage techniques currently available. Authors in [5] [6] provide a comprehensive description of ice storage systems and propose design guidelines.

Many studies have performed field monitoring of ice storage systems. Authors in [7] describe ice storage unit in an 18,000 square feet single story office building in California. The results show the unit's ability to shift the building's peak demand while maintaining the building's cooling requirements. Authors in [8] describe a 20,000 Btu ice storage air conditioning system. The results show ice storage system's total energy consumption being 304.6KWh and conventional air conditioner's being 323.93 KWh. Authors in [9] investigate nine buildings in Iran with ice storage and show significant potential capability to shift a maximum of 33.4% cooling load from peak hours to off-peak hours. Authors in [10] analyze the measured energy performance of partial ice storage system operational in a 4 story (2,000,000 sqft) office building in San Ramon, and a 24-story high rise office building in San Francisco. The results show power savings during peak periods as compared to three types of modeled conventional cooling systems including a single-chiller system, a split system with two equal size smaller chillers and a split system with two unequal units, one twice the capacity of the other. The author in [11] field tests an ice harvester storage system and finds it to show relatively poor energy performance.

Ice storage systems have been modeled and analyzed by several studies. Authors in [12] compare the total energy consumption (including compressors, pumps and condensing fans) of full and partial storage operating strategies for an internal melt ice-on-coil model with conventional cooling system model for an office building in Bangkok. The results show lowest energy consumption for full storage whereas partial storage's energy consumption is 18% more than conventional cooling system and 24% more than full storage. The study also concludes that the compressor Coefficient of Performance (COP) is interrelated to a number of factors such as ambient temperatures, ice percent charge in the ice tank and design of the system. Authors in [13] describe an ice storage system with higher chiller energy consumption than a modeled non-storage system however the overall energy consumption for the ice storage system is less due to downsized pumps and cooling tower and the use of water side economizer cycle. Authors in [14-16] propose optimal control strategies for ice storage systems. These strategies are based either on simplified ice storage system models or include analysis of the cooling system only without consideration of the impacts of the entire building operation and design conditions such as internal gains and building thermal mass effects. Authors in [17] have developed a steady state chiller model with cooling tower, pump and fan to simulate ice storage system operation. Authors in [18] use EnergyPlus ice storage model that takes into account building operations and design conditions to simulate baseloading operation[1] of ice storage systems with storage priority and chiller priority for a small building in Arizona. The results show higher chiller energy consumption for ice storage systems than non-storage cooling system for the design day. Increasing the chiller and tank size for storage priority shows more overall chiller energy consumption but achieves greater peak demand shift.

Authors in [10] point out that few thermal energy storage systems take advantage of daily climatic variations and operating conditions to optimize system charging and discharging strategies. Author in [19] investigates the effects of increasing ice chiller and tank size on the operating cost of the cooling system with an optimized controller. The optimized controller optimizes the pre-cooling strategy utilizing building thermal mass and the charging/discharging rates of ice tank. Authors in [20] establish an analytical method using dynamic programming for optimizing ice storage air conditioning system based on minimum lifecycle cost and storage tank performance. Authors in [21] evaluate relative performance of the conventional control strategies including chiller priority, storage priority and constant proportion with designed optimal control strategy which minimizes energy and demand charges while maintaining occupant comfort. The author in [22] designs an optimum neural network controller for an ice storage system to minimize operating costs. Authors in [23] investigate the performance of four control strategies; one optimal control strategy and three conventional control strategies (chiller priority, storage priority and constant proportion) with respect to changes in operating costs, total energy consumption, building types, Wisconsin weather types, on-peak demand, rate structures, ice storage systems and chiller types. Authors in [24] investigate the thermal storage components sizing and their impacts on the overall

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[1] An efficient chiller meets constant component of a facility's load while a downsized storage chiller is used to level or shift the remaining load.

system cost.

Ice storage tank's charging and discharging has also been investigated by some studies. Author in [25] tests the charging and discharging performance of different manufacturer's ice storage systems. Authors in [26] model an ice-on-coil internal melt storage tank and analyze its charging and discharging processes.

Authors in [27, 28] analyze the ice chiller's efficiency during charging of ice tanks and when providing direct cooling. The results conclude that during direct cooling the chiller's COP is higher than during charging period.

No literature work has been found investigating the impacts of ice storage systems on the chiller energy consumption for large and medium-sized office buildings in diverse climate zones. This thesis bridges the knowledge gap by modeling and simulating large and medium-sized office buildings with conventional non-storage and ice storage cooling systems in diverse climate zones. The chiller energy consumption and peak energy savings as a result of ice storage systems are analyzed in this research. Demand Response Quick Assessment Tool (DRQAT) software tool is used for modeling and simulation purposes. DRQAT uses EnergyPlus as its simulation engine. EnergyPlus takes into account the entire building operation and design conditions including internal loads and building thermal mass. The operating and control strategies of ice storage system investigated in this thesis include full storage and partial storage with storage priority and chiller priority.

2. ICE STORAGE SYSTEMS

This chapter presents an overview of ice storage systems.

2.1. Introduction

Thermal energy storage systems can shift demand from on-peak to off-peak periods by employing building thermal mass or with water chilled system, ice storage system and phase change materials. Without a thermal storage unit, the equipment has to be sized to meet the peak cooling requirements.

Building thermal mass provides significant thermal storage potential and can be used to shift cooling to night time unoccupied periods but the demand savings by pre-cooling are sensitive to occupancy schedule, building construction, climate conditions and control strategy [29].

Chilled water storage uses sensible heat[2] capacity of water (1 Btu/lb ^{0}F) to store cool energy. The practical minimum storage volume for chilled water is approximately 10.7 cubic feet per ton-hour at a 20°F temperature difference between water supplied to storage and returning from load [30]. Although being compatible with existing chillers there disadvantage is the requirement of large storage tanks [31].

Ice storage uses latent[3] heat of fusion of water (144 Btu/lb) at 32^{0}F to store cool. Depending on ice storage technology, storage volume ranges between 2.4 to 3.3 cubic feet per ton-hour [30]. The low chilled water supply temperatures available from ice storage allow the use of cool air distribution, the benefits of which include the ability to use smaller fans and ducts and the introduction of less humid air in occupied spaces [4].

Most common phase change materials store 41 Btu/lb at their freezing/melting point of 47°F with storage volume of 6 cubic feet per ton-hour. The 47°F phase-change point of this material allows the use of standard chilling equipment [30]. The biggest disadvantage is that the tank typically cools the water for the distribution system to only 48–50°F, which accomplishes less dehumidification of the building and requires more pumping energy [4].

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[2] Sensible heat can be perceived by the human senses

[3] Latent heat is heat released or absorbed during phase change without change of temperature.

2.2. Ice Storage System Types and Their Control

Ice storage builds ice by chiller or refrigeration plant during off-peak hours to serve part or the entire on-peak cooling requirement. The latent heat of fusion of water (144 Btu/lb) is the highest among common materials, that is melting or freezing of one pound of ice at 32^0F absorbs or releases 144 Btu of heat. The coolant which is circulated through the ice tanks to make ice is at a temperature of 15^0F to 26^0F. Ice storage systems include:

A. Ice Harvesting

In an ice harvesting system, ice formed on an evaporator surface is periodically released into a tank filled with return water to be cooled by ice. The cooled water is pumped from tank to meet the cooling load. Schematic of an ice harvesting system is available at [32].

B. Ice-on-Coil External Melt

In an ice-on-coil external melt system, a refrigerant or secondary coolant such as glycol is circulated through submerged pipes or tubes on which ice is formed. The ice is melted from the outside by circulating the warm return water over the pipes discharging storage. Schematic of an external melt ice storage system is available at [33]. As the ice melts during the melting cycle its surface area decreases and hence the rate of thermal energy transferred from the ice to the tank water decreases. When approximately 50% ice remains on the tube, the tank's water temperature begins to rise until all of the ice has melted. Suitable applications for external melt systems would be those which have higher loads at the start of the melting cycle and low loads at the end of the melting cycle. For proper tank operation the air agitation system is necessary. The bubbler, a positive displacement air pump is the most essential component which agitates the tank water during initial build up period and tank cool down [34].

C. Ice-on-Coil Internal Melt

Ice is formed on submerged pipes or tubes same way as it is formed in the external melt system. Here unlike the external melt system, ice is melted from the inside by circulating warm coolant through the pipes. The coolant gives away its heat to the ice and is then pumped through building’s cooling system or cools secondary coolant circulating through building’s cooling system. The tank water never leaves the tank. Schematic of an internal melt ice storage system is available at [33]. During the ice melting cycle the leaving coolant temperature first rises as the surface area of the heat exchanger is limited to the inside surface of the melting cylinder of ice, a small annulus of melted ice between the warm coil and 32^0F ice. Later in the melt cycle the ice cylinders break and melt rapidly. Suitable applications for internal melt would be those, which have smaller loads at the start of the melting cycle and higher loads at the end of the melting cycle.

D. Encapsulated Ice

Water freezes and thaws in plastic containers enclosed in a tank as cold or warm coolant is circulated through the tank, conceptually similar to ice in the coil-internal melt system. Dimpled balls about 4 inches in diameter are common plastic containers. These dimples allow for contraction and expansion while the states are being changed between water and ice. The spherical shape allows high heat transfer area per unit of water being frozen. Schematic of an encapsulated ice storage system is available at [35].

The most common commercial technology is the internal melt system. The encapsulated ice system is also suitable for many commercial applications, whereas the ice harvesting and external melt systems are more common in industrial applications. Ice storage can be operated as full or partial storage.

A. Full Storage

In a full storage system, the entire on-peak cooling load is shifted to off-peak period, and the chiller storing the required cooling capacity during off peak period. The cooling load is met by storage and the chiller remains nonoperational during peak demand. The equipment first cost is high due to larger chiller and storage requirements but greatest savings can be achieved. The full storage system is suitable for a system with a short peak period or high demand charges during a peak period.

B. Partial Storage

In a partial storage system, the chiller and storage together meet the on-peak cooling load.

Less electrical demand is shifted to off-peak period by partial storage but smaller chiller and storage is required. Partial storage is more favorable in commercial buildings where occupied and unoccupied periods are of similar durations. There are two types of operating strategies demand limiting and load leveling.

1) Demand limiting: This strategy operates the chiller at a reduced capacity during peak demand. The chiller is controlled to limit the facility demand at the billing meter. Storage requirement and chiller capacity are larger than load leveling operating strategy.

2) Load leveling: In a load leveling operating strategy the chiller runs 24 hours. As long as the load is less than the chiller output, it is met by the chiller only. When the load exceeds the chiller output, the excess is met by storage discharge. This strategy is useful where peak cooling load is much higher than average load. Partial storage can also be used as full storage if the cooling load is small enough, taking care not to deplete the storage before the on-peak period is over.

Partial storage uses chiller and storage priority strategies to divide the load between chiller and storage. For the chiller priority strategy, storage meets the load only when the load exceeds chiller capacity. The chiller operates at full load continuously. For the storage priority strategy, chiller meets the load only when the load exceeds the total storage capacity. The chiller does not operate at its full capacity continuously. A combination of these control strategies may be used.

3. METHODOLOGY

This chapter proposes the methodology to bridge the knowledge gaps identified in Chapter 1.

3.1. Simulation Tool

Demand Response Quick Assessment Tool (DRQAT) version 4.0.0 has been used for the modeling and analysis of the storage unit performance. Demand Response Quick Assessment Tool (DRQAT) has been developed by LBNL's Demand Response Research Center funded by the California Energy Commission's Public Interest Energy Research (PIER) Program and can be downloaded from [1]. Large and medium-sized office buildings with non-storage and ice storage systems have been modeled in Demand Response Quick Assessment Tool (DRQAT) in diverse climate zones. DRQAT provides a graphical user interface and is easier to interact with. It has been designed for simulating large commercial buildings including offices and retail units. The tool uses EnergyPlus as the simulation engine. EnergyPlus computes whole building energy consumption taking into account climate, building form and fabric, internal gains and HVAC systems interactions and is certified to meet ASHRAE 90.1 Appendix G performance requirements. EnergyPlus has inherited simulation characteristics from both BLAST and DOE-2 programs. DRQAT requires simple building input parameters like the number of floors, the length and width of each floor, the window-to-wall ratio (WWR[4]), the building location and orientation, the number of occupants and densities of internal loads (lighting and plug loads). DRQAT also allows users to model HVAC and internal loads schedules such as hourly schedules for internal loads, operating schedules of the HVAC system, zone temperature setpoints and temperature setpoints for chilled water, condenser water and supply air. This avoids the error prone process of writing EnergyPlus input files. Some of DRQAT's output results exploited in this research include the daily and monthly chiller power consumption for conventional and ice storage cooling systems and the daily ice charge and discharge rates for the ice storage systems. However DRQAT models only commercial buildings for California climate zones and the building construction standards that are in compliance with California Title 24 construction standard. In order to

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[4] WWR is the ratio of window area (glass area and frame) to the exterior wall area.

model buildings in cities other than California representing diverse climate zones the weather and building construction files in DRQAT have been modified. The climate data and construction standards for selected cities representing diverse climate zones have been incorporated into DRQAT.

3.2. Climate Zones

The large and medium-sized office buildings have been modeled in diverse climate zones to analyze the chiller energy consumption for ice storage systems. The cities representing the different US climate zones have been selected by [36].

The zones are categorized from very hot zone 1 to very cold zone 8. The sub zones represent moisture content, subzone A represents humid, B represents dry and C represents marine subzone [37].

Zone 1A: Miami, Florida (hot, humid)

Zone 2A: Houston, Texas (hot, humid)

Zone 2B: Phoenix, Arizona (hot, dry)

Zone 3A: Atlanta, Georgia (hot, humid)

Zone 3B-CA: Los Angeles, California (warm, dry), Las Vegas, Nevada (hot, dry)

Zone 3C: San Francisco, California (marine)

Zone 4A: Baltimore, Maryland (mild, humid)

Zone 4B: Albuquerque, New Mexico (mild, dry)

Zone 4C: Seattle, Washington (marine)

Zone 5A: Chicago, Illinois (cold, humid)

Zone 5B: Denver, Colorado (cold, dry)

Zone 6A: Minneapolis, Minnesota (cold, humid)

Zone 6B: Helena, Montana (cold, dry)

Zone 7: Duluth, Minnesota (very cold)

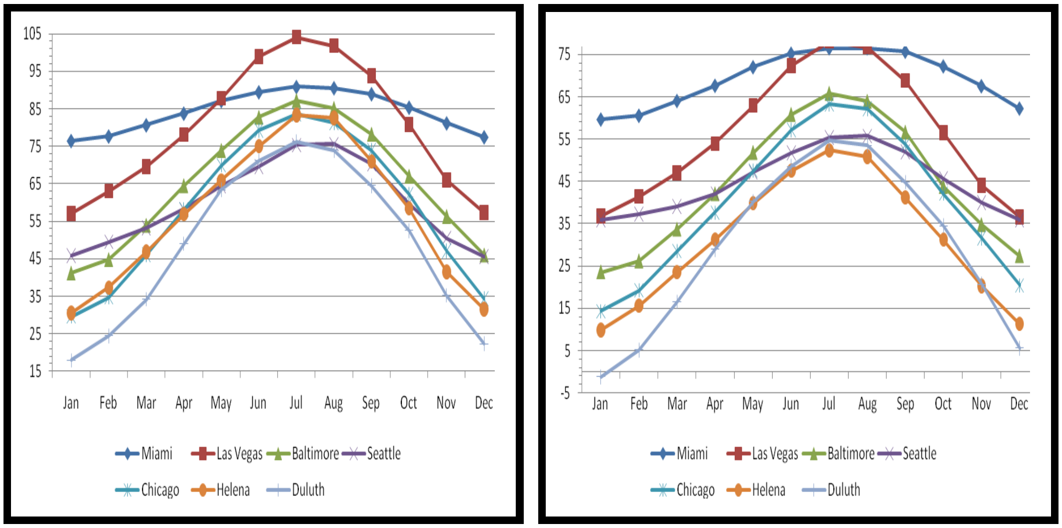
Zone 8: Fairbanks, Alaska (extreme cold)

Some of the above cities have been selected in this thesis for analysis purposes as shown in Table 3-1.

Climate zone	Type	City
1A	Hot and humid	Miami, Florida
3B	Hot and dry	Las Vegas, Nevada
4A	Mild and Humid	Baltimore, Maryland
4C	Marine	Seattle, Washington
5A	Cold and humid	Chicago, Illinois
6B	Cold and dry	Helena, Montana
7	Very cold	Duluth, Minnesota

Table 3-1 Reference Cities Representing US Climate Zones

The weather data for the cities have been obtained from NREL TMY3 dataset which is available for download as EnergyPlus weather format from [38]. The Demand Response Quick Assessment Tool (DRQAT) weather data files have been updated with the TMY3 files for the selected cities representing diverse climate zones. Figure 3-2 shows the average monthly high and low temperatures for the selected cities.



High Temperature

Low Temperature

Figure 3-1 Average Monthly Temperature Range

Source: [39]

Table 3-2 shows the monthly relative humidity (RH) for the selected cities.

Cities	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A
Miami	84	59	84	57	82	56	79	54	80	58	84	65	83	63	85	65	87	66	86	63	85	62	84	60
Chicago	78	70	78	67	79	63	77	57	77	56	79	58	82	59	86	60	85	60	81	58	80	66	80	71
Baltimore	73	57	72	54	72	51	72	49	77	52	77	52	80	53	84	55	85	55	84	53	79	54	75	57
Duluth	77	72	77	67	78	65	76	58	76	56	82	63	86	62	88	66	88	67	82	65	81	72	80	75
Helena	72	64	73	55	73	46	71	39	71	38	73	38	67	31	67	30	72	35	73	43	74	58	73	66
Las Vegas	55	32	52	28	45	23	35	16	32	14	24	11	28	15	34	17	34	17	36	20	46	27	53	32
Seattle	82	74	81	67	83	62	84	58	84	55	83	54	82	49	84	51	87	57	88	67	85	75	83	78

Table 3-2 Average RH (%) Morning and Afternoon

Source: [40]

RH is the amount of water vapor in a mixture of air and water vapor. High RH affects human comfort adversely. A building's cooling system controls both temperature and RH for human comfort.

3.3. Large and Medium-Sized Office Building Models

Large and medium-sized office building construction model details used in this thesis are based on the study conducted by DOE's Building Technologies Program along with PNNL, LBNL and NREL whereby 16 types of Reference Commercial Buildings had been developed covering 70% of US commercial buildings in all US climate zones [36]. The EnergyPlus input files for these reference buildings are available in [41]. The Demand Response Quick Assessment Tool (DRQAT) building construction file, which follows the California Title 24 construction standard, was modified to include the construction details of the DOE reference office buildings (new construction) for the selected cities. Large and medium-sized office building's occupancy, lighting, electric plug loads, HVAC and cooling set point schedules are based on [37] which have been developed through a combination of industry validated assumptions, DOE reference office buildings and PNNL study for medium-sized office buildings. Figures 3-3 and 3-4 show the weekday schedules for the modeled large and medium-sized office buildings.

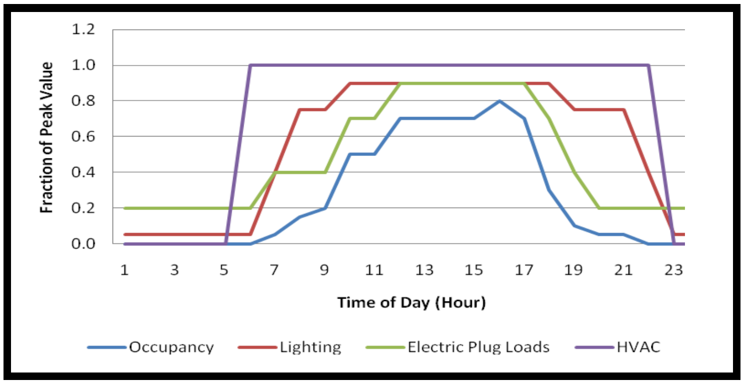


Figure 3-2 Large and Medium-Sized Office Building's Weekday Schedules for Occupancy, Lighting, Electric Plug Loads and HVAC
Source:[37]

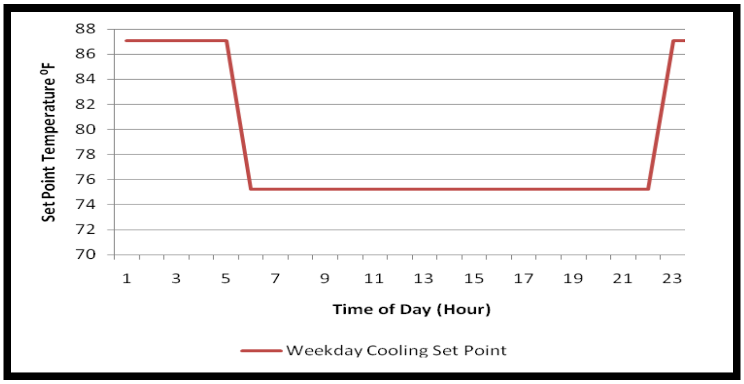


Figure 3-3 Large and Medium-Sized Office Building's Weekday Cooling Set Point Temperatures
Source: [37]

The cooling equipment sizing for both large and medium-sized office buildings for the cities in different climate zones is done by EnergyPlus with a global sizing factor of 1.2 using design day cooling condition based on 0.4% annual percentiles and internal loads scheduled as maximum level on cooling design day.

3.3.1. Large Sized-Office Building Model

The large-sized office building modeled in Demand Response Quick Assessment Tool (DRQAT) is based on DOE reference large-sized office building with minor modifications. A 12-story high-rise office building with an area of 498,588 sqft has been modeled. The building has fixed windows, flat roof with insulation entirely above deck roof and the exterior walls are mass walls consisting of 1-in stucco, 8-in concrete, fiber insulation and ½ in gypsum drywall. The ground floor is modeled as slab on grade construction with carpet pad over 4in thick heavyweight concrete. The building's floors consist of a rectangular core zone with perimeter zones 20 ft deep from exterior walls on each side [37]. The interior walls are modeled as air layer sandwiched between ½ in thick gypsum boards. The interior floors and ceilings are modeled as carpet pads above 4-in thick concrete on metal decking; the ceiling plenums have not been modeled. The internal mass has been modeled with 6-in standard wood. The hydronic Variable Air Volume (VAV) system has been modeled for large-sized office buildings. The modeled large-sized office building's construction parameters are summarized in Table 3-3.

Large-Sized Office Building	
Area	498,588sqft
Number of floors	12
Floor-to-floor height	13ft
Aspect ratio	1.5
Length	240ft
Width	173ft
WWR	38%
Total no. of occupants	2397
Interior Lighting Power Density	1W/sqft
Electric Plug Load Density	1W/sqft

Table 3-3 Large-Sized Office Building's Characteristics

Source: DOE Commercial Reference Buildings [41]

3.3.2. Medium Sized-Office Building Model

The medium-sized office building modeled in Demand Response Quick Assessment Tool (DRQAT) is based on DOE reference medium-sized office building with minor modifications. A 3-story office building with an area of 53,628 sqft has been modeled. The building's windows, roof, interior ceilings and floors, internal mass and ground floor are modeled the same as for large-sized office buildings. However the medium-sized office building has steel framed exterior walls consisting of sheathing, fiber insulation and ½ in gypsum drywall. The building's floors consist of a rectangular core zone with perimeter zones 15-ft deep from exterior walls on each side [42]. The medium-sized office building has a packaged multi-zone VAV air conditioning unit. The modeled medium-sized office building's construction parameters are summarized in Table 3-4.

Medium-Sized Office Building	
Area	53,628sqft
Number of floors	3
Floor-to-floor height	13ft
Aspect ratio	1.5
Length	164ft
Width	109ft
WWR	33%
Total no. of occupants	268
Interior Lighting Power Density	1W/sqft
Electric Plug Load Density	1W/sqft

Table 3-4 Medium-Sized Office Building's Characteristics

Source: DOE Commercial Reference Buildings [41]

3.3.3. Non-Storage Cooling Systems for Large and Medium-Sized Office Buildings

3.3.3.1. Hydronic VAV System for Large-Sized Office Buildings

Large-sized office buildings have been modeled with a hydronic cooling system. Chilled water is used as a cooling medium in a hydronic cooling system to cool the air in the cooling coils in the Air Handling Unit (AHU). Schematic diagram of a hydronic VAV system is available at [43]. The chilled water pump circulates chilled water through the evaporator and the building. The packaged vapor compression cooling system provides cooling to the chilled water and rejects heat to the condenser water. The condenser water pump circulates the condenser water through the condenser and cooling tower. Through direct contact of condenser water and air, heat is rejected to the environment. The cooling effect is further enhanced by evaporation of condenser water. The conditioned space receives air from the AHU. Outside air is mixed with the return air and is filtered and conditioned to the desired temperature in heat exchanger coils supplied with chilled water in the AHU. When the outdoor air has a lower enthalpy than the return air it is economical to use this air for cooling the building than circulating the return air. For the VAV system, the airflow is controlled by the VAV boxes, which may also have reheat coils that provide additional heat when space does not need cooling. The air is supplied to the space by diffusers, which mix the supply air with the room air. The air is supplied at a temperature of 55^0F. The chilled water and condenser water temperature set points are 45^0F and 85^0F respectively, in compliance with ARI 550/590-2003 rating conditions for water chillers [44].

3.3.3.2. Packaged VAV System for Medium-Sized Office Buildings

Medium-sized office buildings have been modeled with a packaged VAV system. In a packaged system air is cooled directly by direct expansion of a refrigerant. The system consists of a compressor, air cooled condenser, DX cooling coil, VAV boxes and zone thermostats. The supply air is cooled and dehumidified directly by the evaporation and expansion of refrigerant inside the DX coil's tubes. The evaporating temperature of the refrigerant is between $37\text{-}50^0$F for comfort air conditioning [45]. The heat is rejected in the condenser coil directly to the ambient air. The refrigerant in the condenser coil comes into indirect contact with the outside air and heat is exchanged from the relatively hot refrigerant to the relatively cooler outside air. Fan forced flow of large volumes of air across the heat exchange coils enhances the heat exchange. In the air handler, return air mixes with outdoor air and is filtered, cooled in the DX coil and passes through the indoor blower and supplied to the space through diffusers. VAV boxes control the airflow in zones. The air is supplied at a temperature of 55^0F. Schematic diagram of a packaged system is available at [43].

3.4. Sizing and Control of Ice Storage Systems

3.4.1. Ice Storage Model in DRQAT

An internal melt ice-on-coil storage system with the chiller located upstream the ice tank has been modeled in Demand Response Quick Assessment Tool (DRQAT); based on EnergyPlus ice storage model which has been tested by [18] and [23].

Schematic diagram of an ice storage system with series flow and chiller upstream the ice tank is available at [6]. Warm return glycol from the building load is pre-cooled by the chiller before entering the storage tank. Chiller operation is efficient because of high operating temperatures. Due to lower storage discharge temperatures, usable portion of the total nominal storage capacity is reduced. On the contrary a downstream chiller maximizes the usable portion of storage capacity but due to lower operating temperatures the chiller efficiency is reduced. The ice storage system is ice-on-coil internal melt with charging temperatures in the range of 22^0F to 26^0F and storage discharge temperatures in the range of 34^0F to 38^0F. At night the cooling coils are bypassed and ice is made by circulating a 25% ethylene glycol and 75% water solution from the chiller at temperature lower than the freezing point of water at about 23^0F (25% glycol freezing point 11.4^0F) through the tubes of ice tank till minimum supply glycol temperature is attained or about 95% of water freezes to ice. If a night load is present after the tanks have been charged, the storage can be bypassed, and chiller meets the cooling load. Since the chiller has to cool the glycol to lower temperatures during charge cycle, unlike 45^0F for conventional cooling system, the chiller capacity is derated to 60% to 70% of nominal capacity. Also the chiller COP decreases and increases the electrical energy needed to produce a unit of cooling. Centrifugal chillers have typical COP rating of 5.9 to 5 for conventional discharge temperatures and 4.1 to 3.5 for ice making temperatures. Chillers with reciprocating and screw compressors have COP rating of 5.4 to 4.1 at conventional temperatures and 3.9 to 2.9 for ice making. Scroll compressor COP rating at standard temperatures is 4.1 to 3.1 and 2.9 to 2.7 at ice making temperature [5].

The ice is discharged during day by circulating and cooling warm glycol solution through the tubes of ice tank. A temperature modulating valve set at 45^0F in a bypass loop around the ice tank mixes warm and cool glycol. The 45^0F glycol enters the air cooling coils and cools the air to 55^0F.

The system can provide under various modes of operation including ice making, cooling by ice only, cooling by chiller only and cooling by ice and chiller. Different glycol temperatures (45^0F, 50^0F and 55^0F) operate the ice storage system at different discharge modes (chiller priority, storage priority and full storage respectively).

The ice charge/discharge rate for the ice storage model is determined by using the equation below:

$Charge/Discharge\ rate\ (kW) = u*storage\ capacity\ (kWh)/\Delta t\ (h)$ [18]

Where "u" is the charge/discharge rate (fraction) evaluated every time step based on the thermal and physical operational constraints of the storage system. Δt is the simulation time interval. The "u" value takes into account the ice storage tank's and chiller's maximum charging capacity.

There are three modes of operation, the dormant mode with "u"=0 when no ice is being made nor the building cooling load is being handled by the ice storage system. In the charging mode "u">0, the chiller makes ice at the charging rate. At every time step Δt the ice level in the tank increases. With the chiller's inlet water temperature calculated from the user defined outlet chiller water temperature hourly schedule and the ice-making load the chiller's electricity consumption is calculated. In the discharge mode "u"<0, the ice is discharged to meet the building's cooling load.

3.4.2. Ice Storage System Sizing and Control

A. Design Day

Ice storage systems are sized for full storage and partial storage operation for the design day. The design temperature and humidity conditions are based on frequency of occurrence. 0.4% design condition has been used which means that 0.4% of the time in a year the outdoor air temperature will be above the design condition. It is advisable to use a conservative selection of design temperatures for cool storage system, then a non-storage system as they have less capacity to recover if design loads are exceeded [5]. Full storage systems can be designed for less extreme design weather conditions since they can operate as partial storage if cooling load exceeds design conditions [5].

B. Cooling Load Profiles

For ice storage system sizing, it is important is to determine the cooling load profile for the design day. The cooling load profiles for the selected cities representing diverse climate zones have been obtained from Demand Response Quick Assessment Tool (DRQAT) by modeling the large and medium-sized office buildings. The cooling load is the rate at which energy is removed at the cooling coil that serves a conditioned space in an air conditioning system. It includes space-cooling load, which is the rate at which heat is removed from spaces to maintain air temperature plus the additional load imposed on the system external to the conditioned spaces including pump heat and heat gains to the storage tank. Chilled water pumping energy appears as load to the cooling system. Pump heat during charging reduces chiller capacity available to be stored while pump heat during discharge increases cooling load. There is also loss of cooling capacity due to heat gains to the storage tank. The cooling loads are either the sensible or latent loads, the sources of which are the occupants of the building, electrical equipment, lighting, infiltration, solar heat gain through windows and heat gain by building envelope. The sensible load causes changes in the dry bulb temperature while the latent affects the moisture content of the conditioned space. Cooling load can be calculated based on the methods described in the ASHRAE Handbook 2001. In order to determine the required storage capacity, total integrated cooling load should be known which must be met by the chiller during its entire period of operation. Also the timing of the load is required to ensure storage capacity would be available when needed.

C. Chiller and Storage Capacities

With the total integrated cooling load, the quick sizing of chiller and storage capacities has been done by using the formulae presented in [5] . For chiller priority the chiller and ice tank sizes were than adjusted to obtain better energy performance.

Total kWh= chiller day capacity + chiller night capacity

*Chiller day capacity= chiller capacity * day hours*

Chiller night capacity= chiller capacity night hours * capacity factor*

Hence

*Total kWh= chiller capacity * (day hours + night hours * capacity factor)*

*Chiller capacity= total kWh/ (day hours + night hours * capacity factor)*

*Storage capacity= total kWh – chiller capacity * day hours*

The capacity factor used is 70%. A system designed for partial storage operation on the design day can be operated as full storage on any other day of the year. Also discharging mode may be storage priority control for a summer design day and chiller priority control for a winter day for the same system.

D. Ice storage Charge and Discharge

Chiller outlet temperature controls the charging and discharging of the ice storage model in Demand Response Quick Assessment Tool (DRQAT). For the charge period the chiller outlet temperature is set at 23^0F. During the discharge period for full storage, storage priority and chiller priority the chiller outlet temperatures are set at 55^0F, 50^0F and 45^0F respectively.

4. SIMULATION RESULTS AND DISCUSSIONS

This section presents general inferences obtained from the simulation results for large and medium-sized office buildings. The cooling load for the modeled office buildings in the selected cities increases as the internal loads increase during the occupied period and outside weather conditions are extreme. As the modeled office buildings have the same occupancy, lighting and electric plug schedules and intensities, their internal loads are same. However the outside weather conditions affect the cooling load. The design day cooling load profiles for the selected cities are shown in Figures 4-1, 4-6, 4-11, 4-16, 4-21, 4-26 and 4-31 for large-sized office buildings and Figures 4-40, 4-45, 4-50, 4-55, 4-60, 4-65 and 4-70 for medium-sized office buildings. The peak period is from noon to 6 PM in the evening after which the occupants start leaving the building and the internal loads start decreasing. Also the cooler evening temperatures lower the cooling load for the office buildings. Total integrated cooling load obtained from the cooling load profile has been used for sizing the ice storage system using equations described in section 3.3.4.2. Tables 4-1, 4-5, 4-9, 4-13, 4-17, 4-21 and 4-25 for large-sized office buildings and Tables 4-30, 4-34, 4-38, 4-42, 4-46, 4-50 and 4-54 for medium-sized office buildings show the size of ice storage systems.

The non-storage chillers remain nonoperational during the unoccupied period and may turn on to maintain the setup temperature. The chiller consumes more energy as the cooling load increases during the occupied period due to increase in internal loads and outside weather conditions as shown in Figures 4-2, 4-7, 4-12, 4-17, 4-22, 4-27 and 4-32 for large-sized office buildings and Figures 4-41, 4-46, 4-51, 4-56, 4-61, 4-66 and 4-71 for medium-sized office buildings.

For the ice storage systems, the ice chiller operates during night-time hours to make ice and also during day-time hours to provide direct cooling. For the full storage system, the entire peak load is met from storage, and the chiller remains nonoperational during this period as shown in Figures 4-3, 4-8, 4-13, 4-18, 4-23, 4-28 and 4-33 for large-sized office buildings and Figures 4-42, 4-47, 4-52, 4-57, 4-62, 4-67 and 4-72 for medium-sized office buildings. For the storage priority system, the storage discharge remains fairly constant during the peak period and the chiller handles the excess cooling load as shown in Figures 4-4, 4-9, 4-14, 4-19, 4-24, 4-29 and 4-34 for large-sized office buildings and Figures 4-43, 4-48, 4-53, 4-58, 4-63, 4-68 and 4-73 for medium-sized office buildings. For the chiller priority system, the chiller power consumption also remains fairly constant during the entire day and any excess load during the peak period is met by the storage discharge as shown in Figures 4-5, 4-10, 4-15, 4-20, 4-25, 4-30 and 4-35 for large-sized office buildings and Figures 4-44, 4-49, 4-54, 4-59, 4-64, 4-69 and 4-74 for medium-sized office buildings.

The internal-melt ice storage system's charging and discharging processess have been discussed in [26]. The charge rate includes 4 stages; stage 1 when sensible heat exchange causes water to cool down, stage 2 when the ice cylinders grow concentric with tube, stage 3 when constrained ice formation causes ice cylinders to overlap and stage 4 when all water is frozen. The charge rate is high when water temperatures are falling and decreases when ice cylinders start overlapping as heat transfer is restricted. The discharge rate rises gradually and then it is steady for most of the time and later starts decreasing. During an ice discharge period, the ice closest to tube melts first, so the discharge starts gradually, the discharge rate during ice melt in the ice cylinder is almost steady when glycol's inlet temperature and flow rate are fixed. Next the ice cylinders break from their weakest point and move up due to low density, during this phase the ice discharge is steady as well. Once the ice cylinders break into pieces the heat exchange rate increases. As the water temperature starts to rise, the storage's discharge rate decreases. The charging level - whether the ice cylinders are non-overlapping or partially overlapping or all water in the tank is frozen - decides the discharging process. Figures 4-3 to 4-5, 4-8 to 4-10, 4-13- 4-15, 4-18 to 4-20, 4-23 to 4-25, 4-28 to 4-30 and 4-33 to 4-35 for large-sized office buildings and Figures 4-42 to 4-44, 4-47 to 4-49, 4-52 to 4-54, 4-57 to 4-59, 4-62 to 4-64, 4-67 to 4-69 and 4-72 to 4-74 for medium-sized office buildings verify this charge/discharge phenomenon.

The storage systems have higher chiller energy consumption than a non-storage system as shown in Tables 4-2, 4-3, 4-6, 4-7, 4-10, 4-11, 4-14, 4-15, 4-18, 4-19, 4-22, 4-23, 4-26 and 4-27 for large-sized office buildings and Tables 4-31, 4-32, 4-33, 4-34, 4-37, 4-38, 4-41, 4-42, 4-45, 4-46, 4-49, 4-50, 4-53 and 4-54 for medium-sized office buildings. This is because the ice chiller operates during the night making ice unlike the non-storage system which may operate during off-hours only to meet any night load. For the ice storage systems during the ice making mode the evaporator temperatures are low thereby reducing the chiller COP[5] although this is compensated to some extent by lower nighttime temperatures.

The chiller energy consumption of a full storage system can be higher than that of a partial storage system due to the charging of a large ice tank at lower evaporator temperatures with reduced COP but the benefit is that during peak hours the chiller remains nonoperational.

Storage priority systems also have to charge ice tanks smaller than needed for full storage but larger than chiller priority. These systems make ice at lower evaporator temperatures with reduced chiller COP and provide direct cooling during peak period to meet any excess load. Higher condenser temperatures are needed for ice discharge.

The small-sized chiller priority system has to charge a comparatively smaller ice tank. The chiller operates at night making ice at reduced COP and provides direct cooling during the entire occupied period at COPs slightly higher from the nighttime operating COPs. Any excess load during a peak period is met by storage discharge.

4.1. Large-Sized Office Buildings Results and Discussions

This sub-section presents the simulation results and discussions for large-sized office buildings. Large-sized office building's non-storage system is a hydronic system with cooling tower which is a latent heat exchanger. The magnitude of heat exchange between the condenser water and ambient air is a function of the quantity of water that is evaporated which is primarily a function of the RH of the outside air. If the outside RH is higher than less evaporation of water takes place and condenser water temperature will be high which reduces the chiller COP. For every 2 degrees of sub cooling which is condensing the refrigerant beyond what is required for condensing process causes 1% increase in refrigeration capacity [46] therefore lower condenser water temperatures are needed. Also the extreme day

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[5] COP=$\frac{T_e}{T_c - T_e}$

conditions increase the condenser water temperature.

The ice storage system has a water cooled condenser hence the evaporative cooling of condenser water is affected by RH and ambient temperatures. Higher RH and ambient temperatures will increase the ice chiller energy consumption. Nighttime chiller operation is further derated due to lower evaporator temperatures.

The outside fresh air brought into the building with high RH will increase the latent cooling load. As the outside temperatures increase more heat energy is transmitted through building envelope and windows, increasing the sensible cooling load.

A. Miami

Figure 4-1 shows the cooling load profile for July 21st, the design day for Miami.

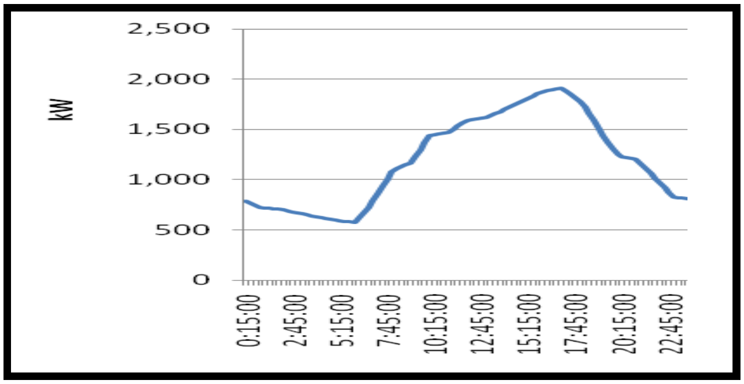

Figure 4-1 Miami Large-Sized Office Building Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-1.

Table 4-1 Miami Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
31,210	2040	112	1576	56	1100	25

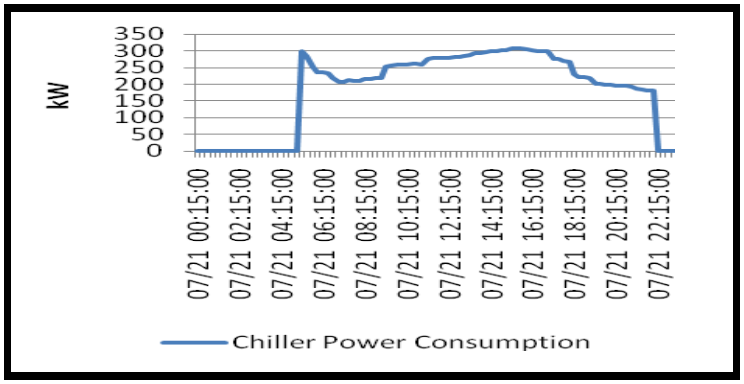

Figure 4-2 Miami Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

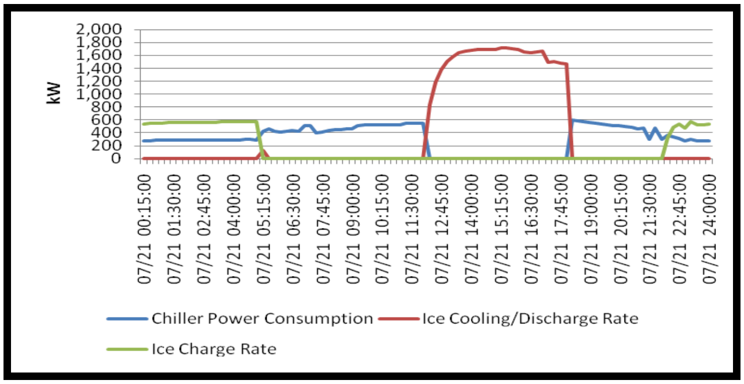

Figure 4-3 Miami Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

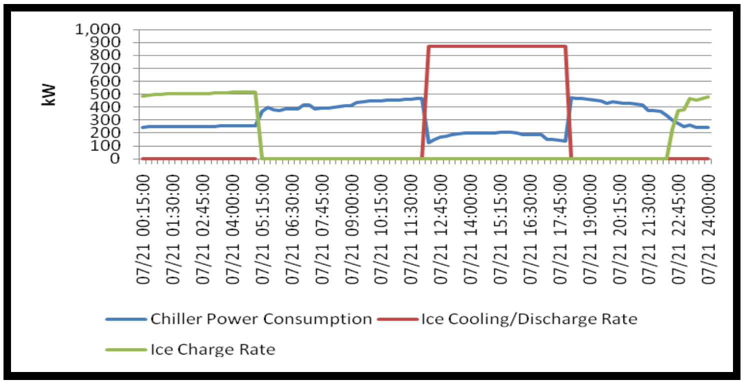

Figure 4-4 Miami Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

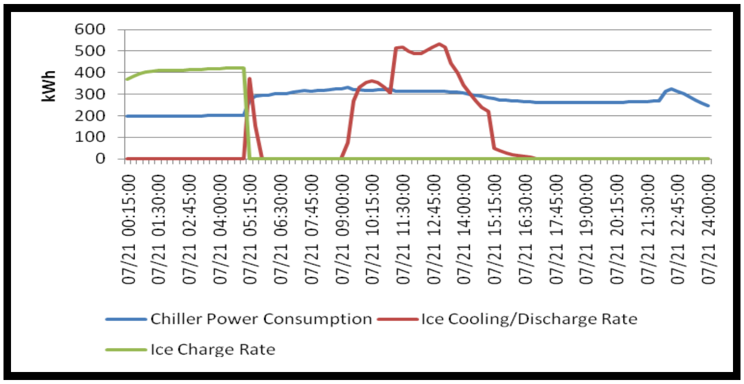

Figure 4-5 Miami Large-Sized Office Building: Chiller Power Consumption Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-2 shows the design day chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-3 to 4-5 show the design day chiller energy consumption and ice charge and discharge rates for the ice storage systems.

Table 4-2 Miami Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,691	4,267	Jun=136,221 July=144,047 Aug=138,109 Sep=136,678

Table 4-3 Miami Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
7,391	Jun=282,476 July=299,283 Aug=289,411 Sep=285,714	7,530	Jun=261,192 July=275,619 Aug=266,714 Sept=262,706	6,530	Jun=232,334 July=242,657 Aug=237,999 Sept=231,533

Tables 4-2 and 4-3 show higher chiller consumption for the ice storage systems than the non-storage system. Chiller energy consumption for the full storage system is slightly lower than the storage priority system for the design day. This is due to the chiller operation during peak hours for the storage priority system when the ambient temperatures and RH both are high. July and August are the hottest months in Miami, Tables 4-2 and 4-3 show high chiller energy consumptions for these months for both the non-storage and the ice storage systems.

Table 4-4 Miami Large-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Chiller Energy Consumption During Peak Hours (kWh)	1,753	0	1,085	1,714

Table 4-4 shows the chiller energy consumption during peak hours from noon to 6 PM in the evening on the design day is higher for the non-storage system than that of the ice storage systems. However the chiller energy consumption for chiller priority with chiller operational throughout the peak period and non-storage system is almost comparable as both have water cooled condensers and both face the issue of high RH and ambient temperatures.

B. Las Vegas

Figure 4-6 shows the cooling load profile for July 21st, the design day for Las Vegas.

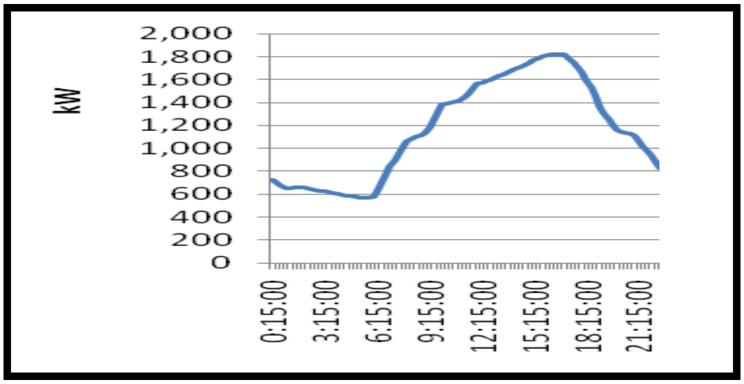

Figure 4-6 Las Vegas Large-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-5.

Table 4-5 Las Vegas Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
29,875	1953	108	1509	53	1000	25

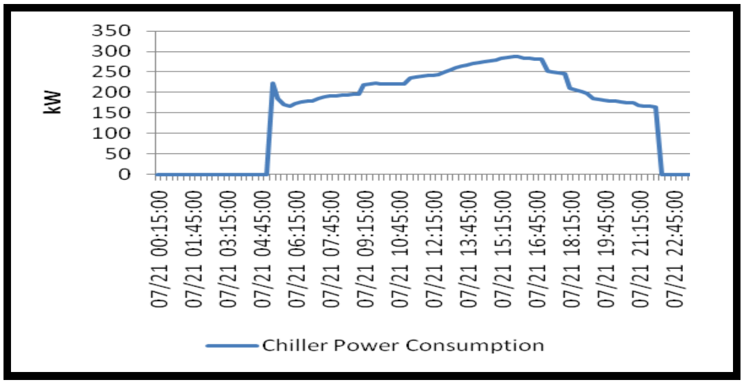

Figure 4-7 Las Vegas Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

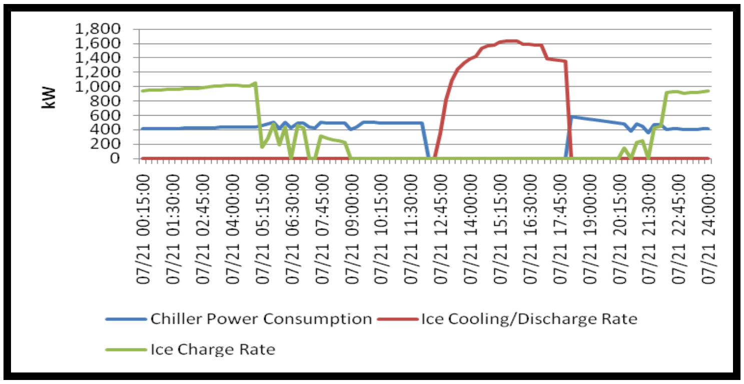

Figure 4-8 Las Vegas Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

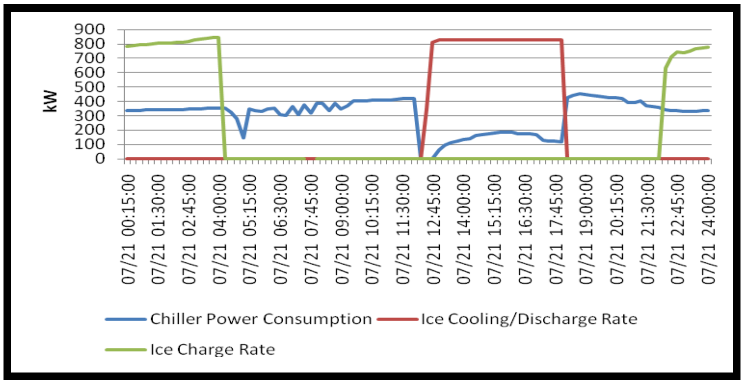

Figure 4-9 Las Vegas Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

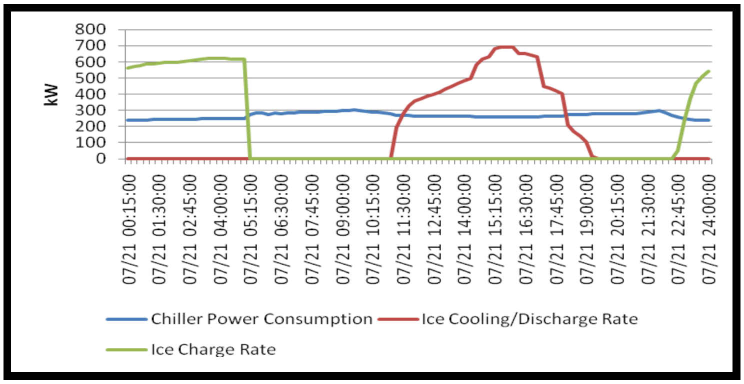

Figure 4-10 Las Vegas Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-7 shows the design day chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-8 to 4-10 show the design day chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-6 and 4-7 show higher chiller energy consumption for the ice storage systems than the non-storage system.

Table 4-6 Las Vegas Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,580	3,762	Jun=124,337 July=135,216 Aug=131,872 Sep=119,115

Table 4-7 Las Vegas Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
8,286	Jun=265,450 July=294,064 Aug=287,171 Sep=260,988	7,351	Jun=243,173 July=263,866 Aug=258,918 Sept=237,264	6,378	Jun=203,093 July=224,707 Aug=220,641 Sept=197,773

Las Vegas has high temperatures in June, July and August, July being the hottest month. Tables 4-6 and 4-7 show high chiller energy consumption in the month of July for both the non-storage and the ice storage systems.

Table 4-8 Las Vegas Large-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	1,606	0	769	1,579

Table 4-8 shows the chiller energy consumption during the peak hours on the design day is higher for the non-storage system than the ice storage systems.

C. Baltimore

Figure 4-11 shows the cooling load profile for July 21st, the design day for Baltimore.

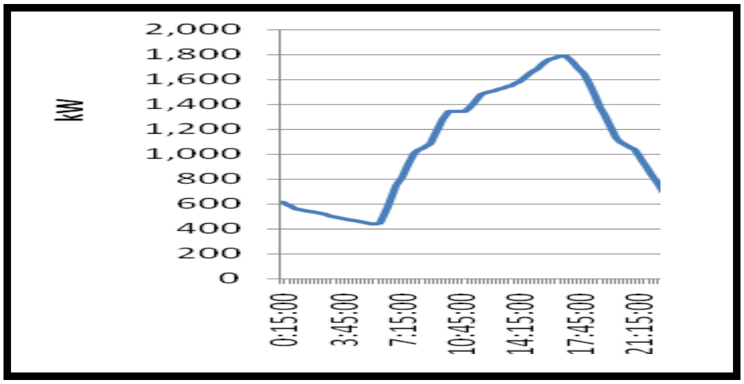

Figure 4-11 Baltimore Large-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-9.

Table 4-9 Baltimore Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
27,970	1828	101	1413	50	950	25

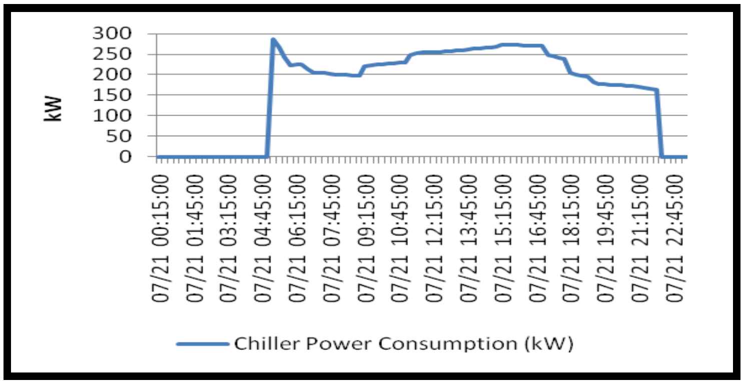

Figure 4-12 Baltimore Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

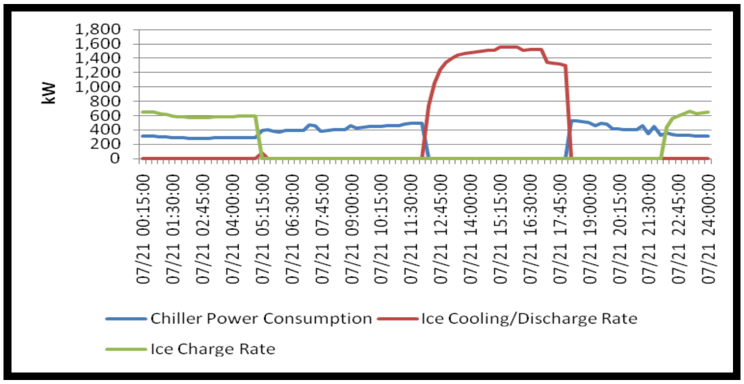

Figure 4-13 Baltimore Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

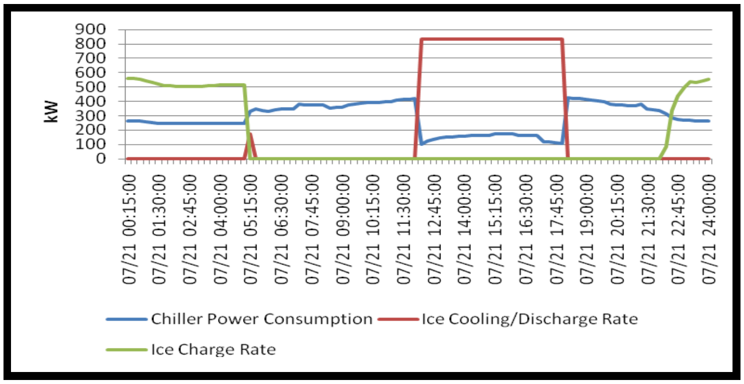

Figure 4-14 Baltimore Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

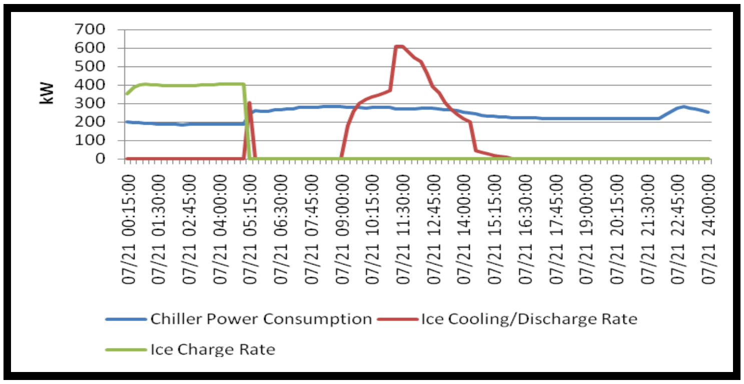

Figure 4-15 Baltimore Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-12 shows the chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-13 to 4-15 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-10 and 4-11 show higher chiller energy consumption for the ice storage systems than the non-storage system.

Table 4-10 Baltimore Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,571	3,864	Jun=114,193 July=124,315 Aug=120,831 Sept=107,928

Table 4-11 Baltimore Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
6,901	Jun=238,064 July=262,942 Aug=259,332 Sept=209,446	6,850	Jun=217,763 July=241,953 Aug=236,091 Sept=188,922	5,783	Jun=184,948 July=209,103 Aug=205,503 Sept=161,899

Tables 4-10 and 4-11 show July and August with higher chiller energy consumption as they are the hottest months in Baltimore.

Table 4-12 Baltimore Large-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	1,571	0	894	1,527

Table 4-12 shows more chiller energy is consumed by the non-storage system during peak hours on the design day than the ice storage systems.

D. Seattle

Figure 4-16 shows the cooling load profile for Aug 21st, the design day for Seattle.

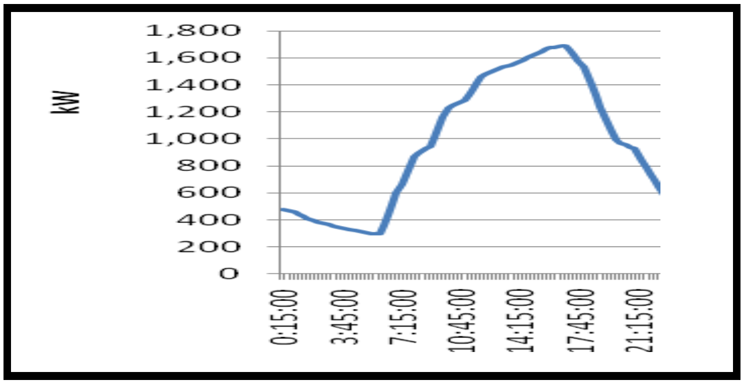

Figure 4-16 Seattle Large-Sized Office Building: Cooling Load Profile on Design Day, Aug 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-13.

Table 4-13 Seattle Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
25,327	1655	91	1279	45	500	15

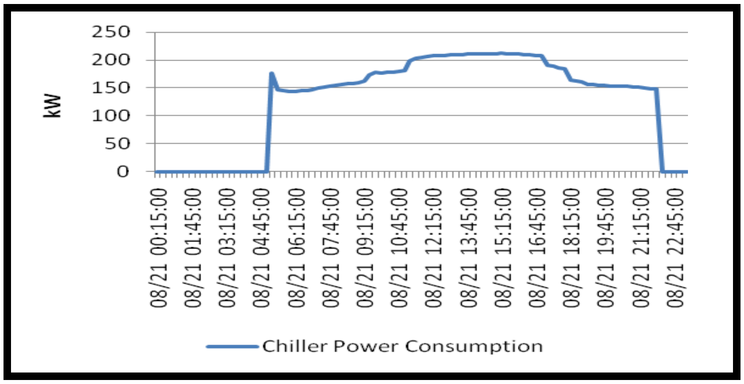

Figure 4-17 Seattle Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, Aug 21st

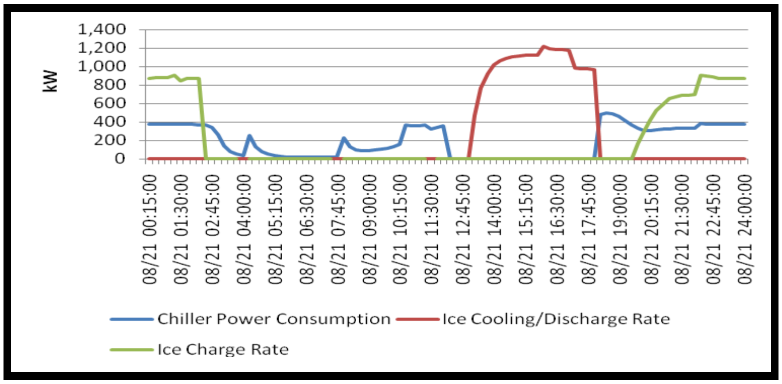

Figure 4-18 Seattle Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, Aug 21st

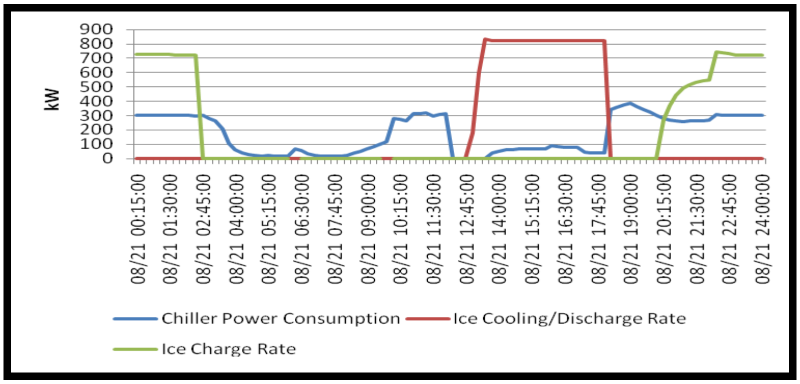

Figure 4-19 Seattle Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, Aug 21st

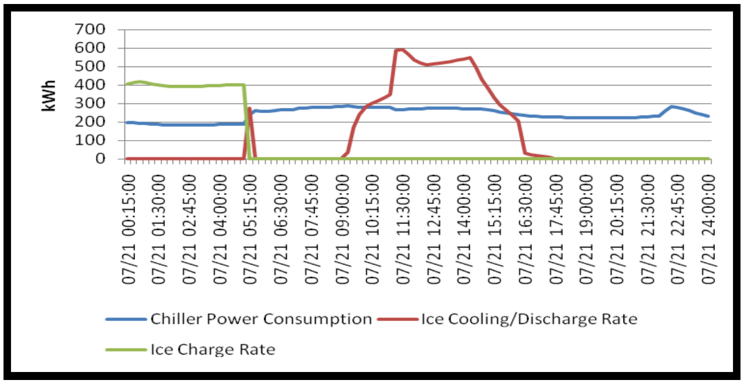

Figure 4-20 Seattle Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, Aug 21st

Figure 4-17 shows the chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-18 to 4-20 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-14 and 4-15 show higher chiller energy consumption for the warmest month in Seattle, August. The tables also show only slightly higher chiller energy consumption for full storage and storage priority than the non-storage system for the summer season except in August. For chiller priority, the chiller energy consumption for the months of June, July and Sept are actually lower than that of the non-storage system and only slightly higher in August. This is due to the fact that Seattle has mild climate during the summer season and the night and day temperature difference is also limited except in August.

Table 4-14 Seattle Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non-Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,166	3,019	Jun=93,786 July=105,201 Aug=106,246 Sept=94,937

Table 4-15 Seattle Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
4,502	Jun=117,685 July=115,535 Aug=180,916 Sept=106,072	4,071	Jun=107,960 July=142,892 Aug=164,098 Sept=96,309	3,152	Jun=83,518 July=103,999 Aug=109,667 Sept=75,890

Table 4-16 Seattle Large-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	Full Storage	Partial Storage: Storage Priority	Partial Storage: Chiller Priority
Energy Consumption During Peak Hours (kWh)	1,237	0	282	758

Table 4-16 show higher chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

E. Chicago

Figure 4-21 shows the cooling load profile July 21st, the design day for Chicago.

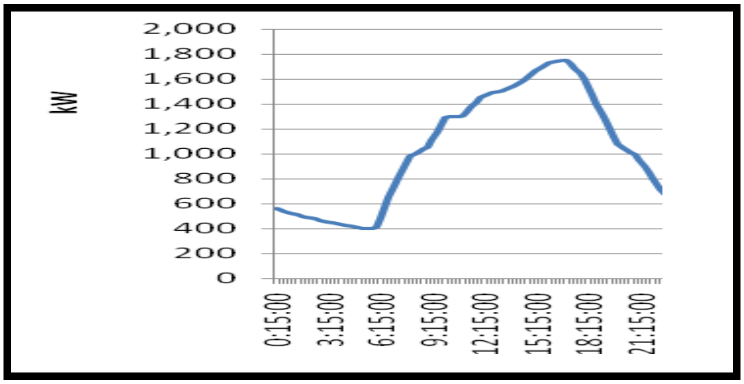

Figure 4-21 Chicago Large-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-17.

Table 4-17 Chicago Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
27,012	1766	97	1364	48	835	15

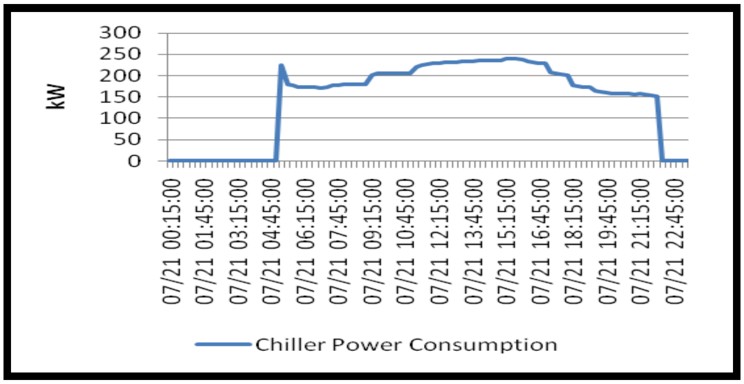

Figure 4-22 Chicago Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

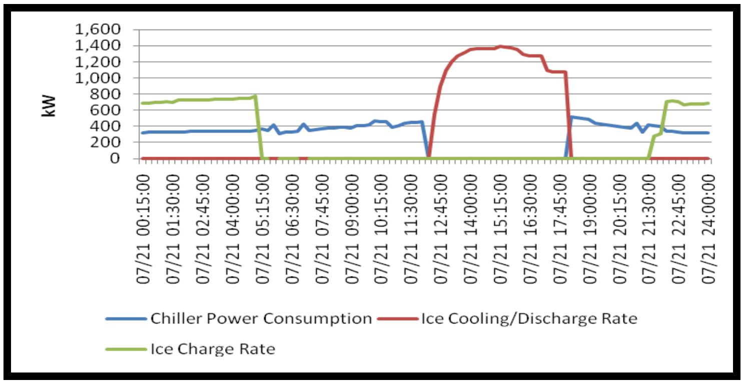

Figure 4-23 Chicago Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

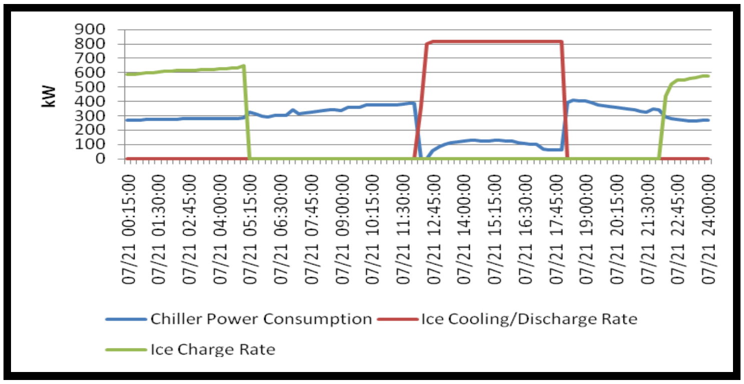

Figure 4-24 Chicago Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

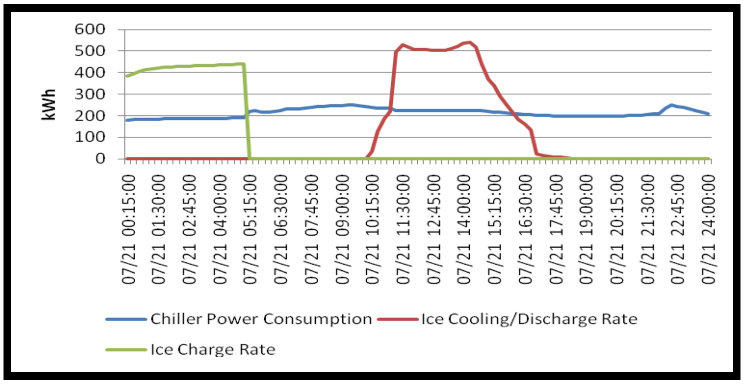

Figure 4-25 Chicago Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-22 shows the chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-23 to 4-25 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems.Tables 4-18 and 4-19 show higher chiller energy consumption for the ice storage systems than the non-storage system.

Table 4-18 Chicago Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,318	3,378	Jun=108,622 July=120,729 Aug=113,036 Sept=101,788

Table 4-19 Chicago Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
6,804	Jun=205,932 July=244,810 Aug=241,026 Sept=177,270	6,371	Jun=187,205 July=226,908 Aug=216,376 Sept=162,256	5,124	Jun=157,907 July=177,919 Aug=176,807 Sept=134,533

Tables 4-18 and 4-19 show high chiller energy consumption for July and August, the warmest months in Chicago, for both the non-storage and the ice storage systems.

Table 4-20 Chicago Large-Sized Office Building: Design Day Chiller Energy during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	1,375	0	572	1,292

Table 4-20 shows higher chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

F. Helena

Figure 4-26 shows the cooling load profile for July 21st, the design day for Helena.

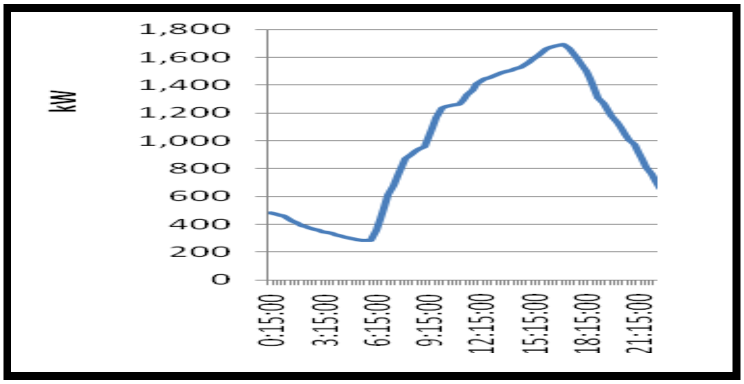

Figure 4-26 Helena Large-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-21.

Table 4-21 Helena Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
25,408	1661	91	1283	45	800	15

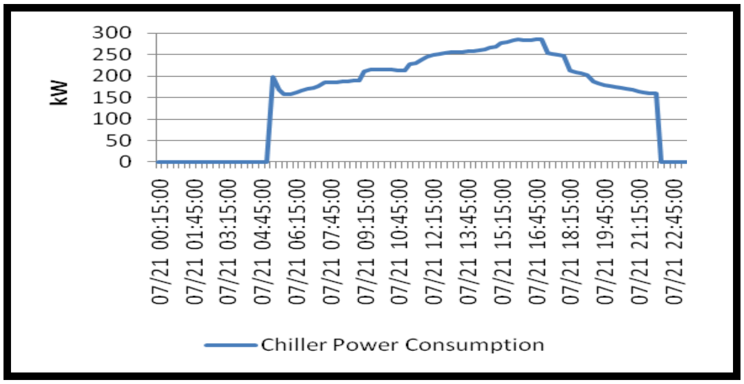

Figure 4-27 Helena Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

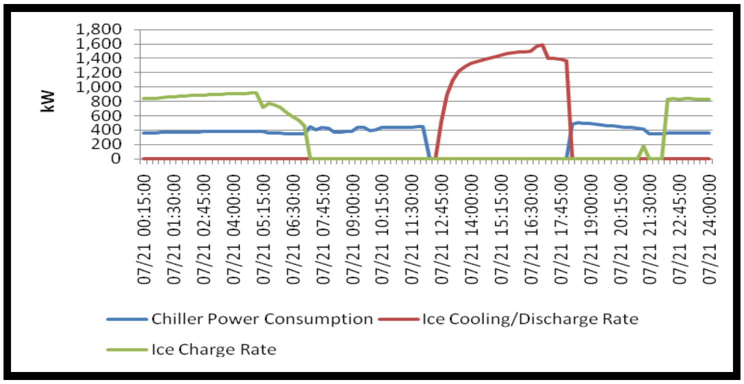

Figure 4-28 Helena Large-Sized Office Building: Chiller Power Consumption and Charge/Discharge Rate for Full Storage System on Design Day, July 21st

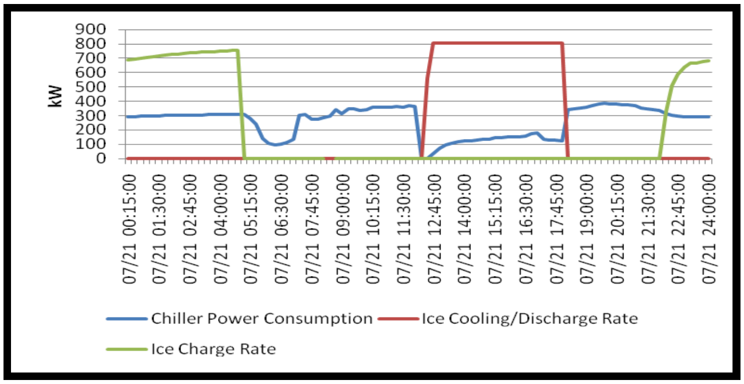

Figure 4-29 Helena Large-Sized Office Building: Chiller Power Consumption and Charge/Discharge Rate for Storage Priority on Design Day, July 21st

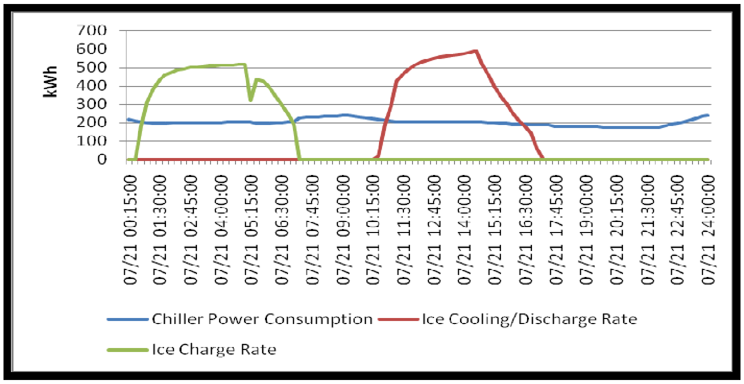

Figure 4-30 Helena Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-27 shows the chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-28 to 4-30 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-22 and 4-23 show higher chiller energy consumption for the ice storage systems than the non-storage system. For chiller priority, in Sept, the chiller energy consumption is lower than the non-storage system. This is due to the cooler temperatures in Sept. The cooler night temperatures improve the charging of the small ice tank. During day, storage discharge further reduces the chiller operation.

Table 4-22 Helena Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,566	3,682	Jun=102,158 July=112,095 Aug=107,234 Sept=97,694

Table 4-23 Helena Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Storage Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
7,165	Jun=149,269 July=207,671 Aug=169,655 Sept=119,558	6,231	Jun=136,885 July=188,111 Aug=155,174 Sept=109,933	4,843	Jun=116,192 July=157,356 Aug=132,606 Sept=91,827

Table 4-24 Helena Large-Sized Office Building: Design Day Chiller Energy during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	1,587	0	711	1,182

Table 4-24 shows higher chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

G. Duluth

Figure 4-31 shows the cooling load profile for July 21st, the design day for Duluth.

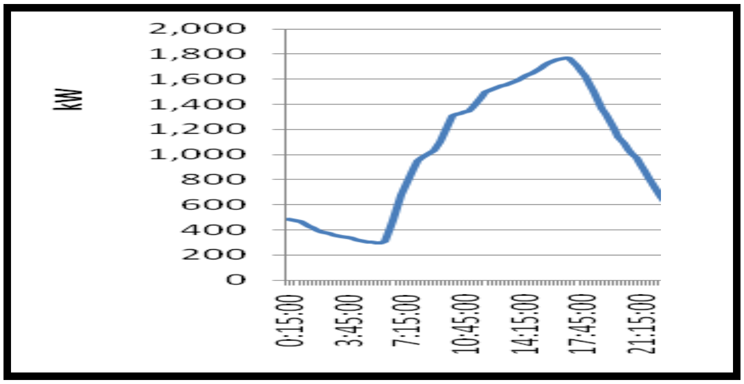

Figure 4-31 Duluth Large-Sized Office Building: Cooling Load Profile for Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-25.

Table 4-25 Duluth Large-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
26,574	1737	96	1342	47	800	15

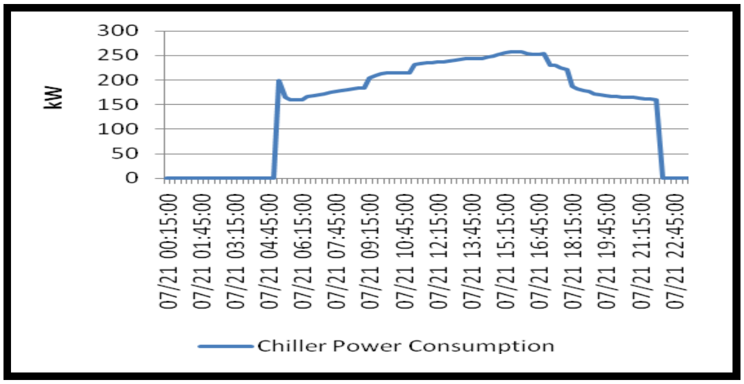

Figure 4-32 Duluth Large-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

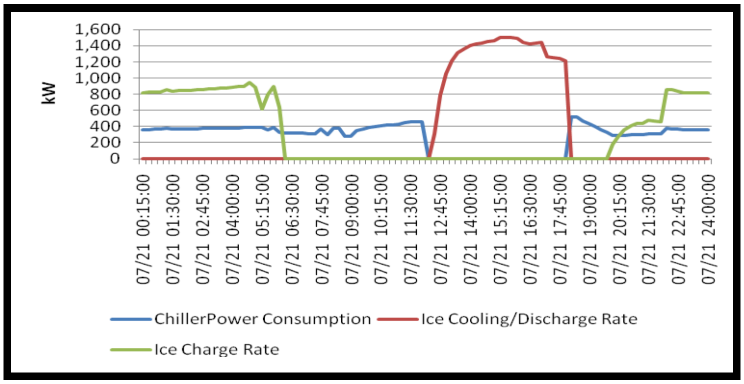

Figure 4-33 Duluth Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

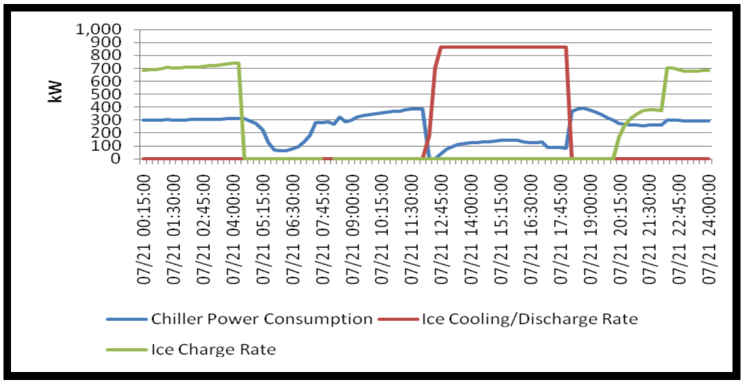

Figure 4-34 Duluth Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

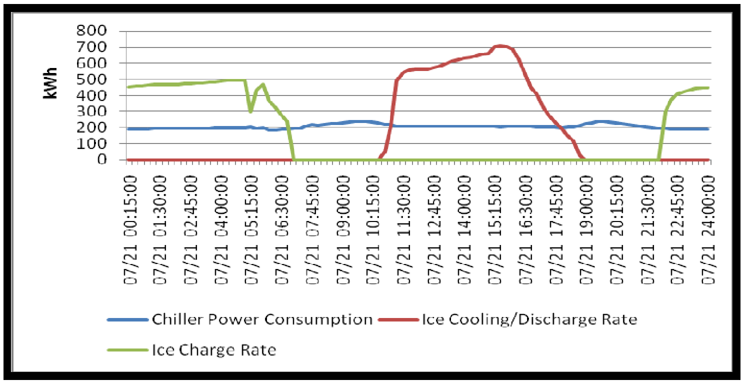

Figure 4-35 Duluth Large-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-32 shows the chiller energy consumption for the non-storage system (hydronic cooling system). Figures 4-33 to 4-35 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems.Tables 4-26 and 4-27 show higher chiller energy consumption for the ice storage systems than the non-storage system. For storage and chiller priorities, in Sept, the chiller energy consumption is lower than the non-storage system. Same reasoning can be given for this observation as explained for Helena.

Table 4-26 Duluth Large-Sized Office Building: Chiller Energy Consumption for Non-Storage System

	Non Storage	
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
1,419	3,498	Jun=106,262 July=112,920 Aug=110,467 Sept=99,199

Table 4-27 Duluth Large-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
6,618	Jun=149,478	5,816	Jun=138,631	4,954	Jun=111,675
	July=187,840		July=168,429		July=138,937
	Aug=173,560		Aug=159,177		Aug=735,349
	Sept=106,315		Sept=96,946		Sept=82,341

July and August have high temperatures with high chiller energy consumption.

Table 4-28 Duluth Large-Sized Office Building: Design Day Chiller Energy during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	1,466	0	630	1,243

Table 4-28 shows higher chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

Table 4-29 provides a comparison of the chiller energy consumption for the design day and during peak hours, noon to 6 PM for the cities representing diverse climate zones.

Table 4-29 Large-Sized Office Buildings: Design Day and Peak Hours Chiller Energy Consumption for Non-Storage and Ice Storage Systems in Diverse Climate Zones

	Non-Storage (kWh)	**Full Storage (kWh)**	**Partial Storage: Storage Priority (kWh)**	**Partial Storage: Chiller Priority (kWh)**
	Design Day (24 Hours) Chiller Energy Consumption			
Miami	4267	7391	7530	6530
Las Vegas	3762	8286	7351	6378
Baltimore	3864	6901	6850	5783
Seattle	3019	4502	4071	3152
Chicago	3378	6804	6371	5124
Helena	3682	7165	6231	4843
Duluth	3498	6618	5816	4954
	Peak Hours (Noon to 6 PM) Chiller Energy Consumption			
Miami	1753	0	1085	1714
Las Vegas	1606	0	769	1579
Baltimore	1571	0	894	1527
Seattle	1237	0	282	758
Chicago	1375	0	572	1292
Helena	1587	0	711	1182
Duluth	1466	0	630	1243

It can be seen that although the chiller energy consumption for the 24-hour design day is higher for ice storage systems due to their day and night operation but they are able to achieve peak energy savings. The full storage system in Miami, for example consumes 73% more chiller energy than the hydronic cooling system. However, during peak hours the chiller operation is completely eliminated. For the storage priority system in Miami, although the peak demand (between noon and 6PM) cannot be shifted entirely, the results show slightly higher chiller energy consumption than that of the full storage system. For the chiller priority system in Miami, the chiller energy consumption is less than that of both the full storage and storage priority systems. However, the peak demand shifting is almost insignificant when compared with the conventional hydronic cooling system. It is also observed that for Seattle, chiller priority achieves more peak energy savings, 39% as compared to the hydronic cooling system, than in the other climate zones. Chiller priority in Helena achieves the next highest peak energy savings, 26%. This is followed by Duluth at 15%.

Figure 4-36 compares the chiller energy consumption for non-storage systems for the selected cities. Table 3-2 and Figure 3-2 have been referred for average temperatures and RH.

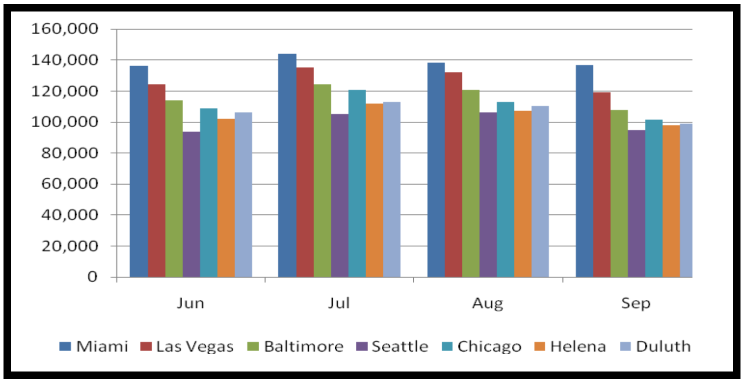

Figure 4-36 Large-Sized Office Building: Monthly Chiller Energy Consumption Non Storage System in Diverse Climate Zones

Non-storage cooling system has water cooled condeners, high ambient temperatures increase condenser water temperatures and high RH lowers the evaporative cooling of condenser water thereby decreasing the chiller COP. High ambient temperatures and RH also increase the building cooling load. Miami has high RH and temperatures among all except for Las Vegas whose temperatures are higher than Miami. With high RH and temperatures Miami has the highest chiller energy consumption for the summer season as shown in Figure 4-36. Las Vegas has low RH as compared to all the reference cities but its temperatures for the summer season are extremely high, the high temperatures require more chiller energy consumption. Baltimore has RH lower than Miami but higher than Las Vegas, its temperatures are lower than both Miami and Las Vegas as a result the chiller energy consumption is lower than Miami and Las Vegas. Chicago with its high humidity and temperatures follows next. Seattle with its moderate temperatures has lower chiller energy cosnumption than all. Helena has temperatures higher than Duluth but Duluth on the other hand has higher RH hence both cities having comparable chiller energy consumption for the summer season.

Figures 4-37, 4-38 and 4-39 compare the chiller energy consumption for the ice storage systems for the selected cities.

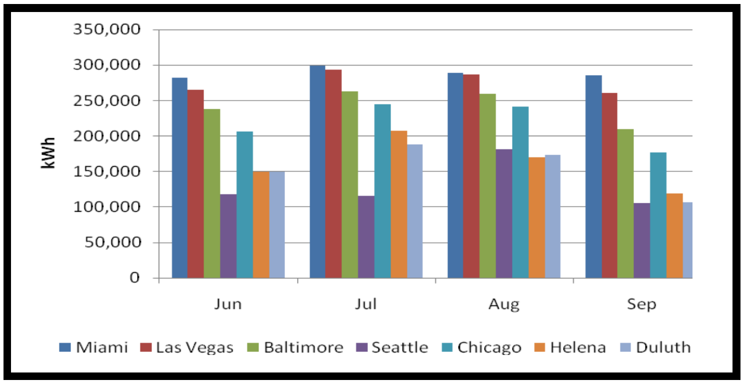

Figure 4-37 Large-Sized Office Building: Monthly Chiller Energy Consumption for Full Storage System in Diverse Climate Zones

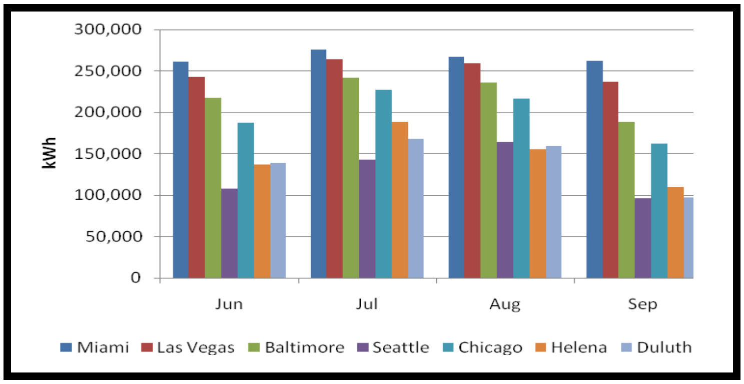

Figure 4-38 Large-Sized Office Building: Monthly Chiller Energy Consumption for Partial Storage: Storage Priority System in Diverse Climate Zones

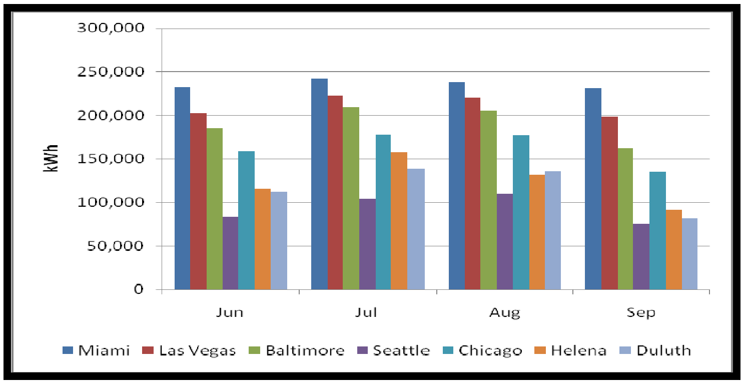

Figure 4-39 Large-Sized Office Building: Monthly Chiller Energy Consumption for Partial Storage: Chiller Priority System in Diverse Climate Zones

For the ice storage systems the chiller makes ice at night and provides direct cooling during day. Chiller priority has to provide more direct cooling than full storage and storage priority during peak hours. Ice storage systems also have water cooled condensers, high ambient temperatures increase condenser water temperatures and high RH lowers the evaporative cooling of condenser water thereby decreasing the chiller COP. Miami has high temperatures and the variations between night and day temperatures are also small. Hence with high temperatures and RH chiller energy is high both for ice making and direct cooling period. Las Vegas has extremely high temperatures during the day but night temperatures are much lower. Hence chiller energy consumption for ice making may be less but during the day the direct cooling provided by the chiller consumes higher energy. Baltimore also has high temperatures and RH and day and night temperature variations are also small. This results in higher chiller energy consumption but lower than that of Miami and Las Vegas.

Chicago has warm climate during summer and day and night temperature variations are also limited. Chicago has higher chiller energy consumption than Seattle, Helena and Duluth due to higher temperatures and RH. Seattle has mild climate during summer and the day and night tempertaure variations are also limited. August is the warmest month in Seattle and in August Seattle's night temperatures are slightly higher than Duluth and Helena. Therefore the chiller energy consumption in Seattle is higher than that in Duluth and Helena due to more energy needed for ice making. For the same month, chiller priority consumes less energy than Helena and Duluth since a small ice tank has to be charged during night. Helena and Duluth have mild climate during summer. Helena has higher day time temperatures but cooler night temperatures. Duluth has day time tempertaures lower than Helena but the night and day time tempertaure variations are small. Also Duluth has higher RH than Helena. This results in both Helena and Duluth having comparable chiller energy consumption for ice storage systems. However in July Helena's temperatures are much higher than Duluth resulting in slightly higher chiller energy consumption.

4.2. Medium-Sized Office Buildings Results and Discussions

This sub-section presents the simulation results and discussions for medium-sized office buildings. The air cooled condenser for medium-sized office building's air cooled system is a sensible heat exchange device, where the magnitude of heat exchange between the refrigerant in the condenser coil and outside air is a function of the temperature difference between the refrigerant and the outside air dry bulb temperature, high outside dry bulb temperatures can increase chiller energy consumption. With high ambient air temperature, the condensing temperature[6] increases and net cooling capacity decreases by about 2% for every 5°F increase in condensing temperature[46]. Also the fresh air brought inside the building with high RH increases the latent cooling load. The high outside temperatures also increase the building's sensible heat load due to heat gain through building envelope and windows.

Medium-sized office buildings have steel framed exterior walls. Steel is a good conductor of heat energy, a metal building freely transfers heat energy in and out of building. The fiber insulation used can resist heat gain by conduction and convection but has little affect on radiant heat gain. Radiant heat can account for up to 70% of a building's overall heat gain [47]. Condensation can also occur when there is considerable temperature difference outside the building. In humid climate zones moisture can be trapped within the fiberglass insulation causing its thermal resistance to drop as water is a good conductor of heat.

Ice storage systems have water cooled condenser hence the evaporative cooling of condenser water is affected by RH.

A. Miami

Figure 4-40 shows the cooling load profile for July 21st, the design day for Miami.

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[6] The condensing temperature is the temperature at which the refrigerant gas will condense to a liquid, at a given pressure

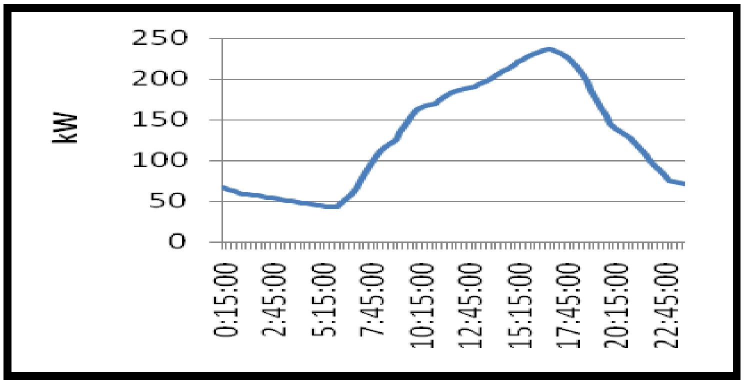

Figure 4-40 Miami Medium-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-30.

Table 4-30 Miami Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
3,431	224	12	173	6	130	2.5

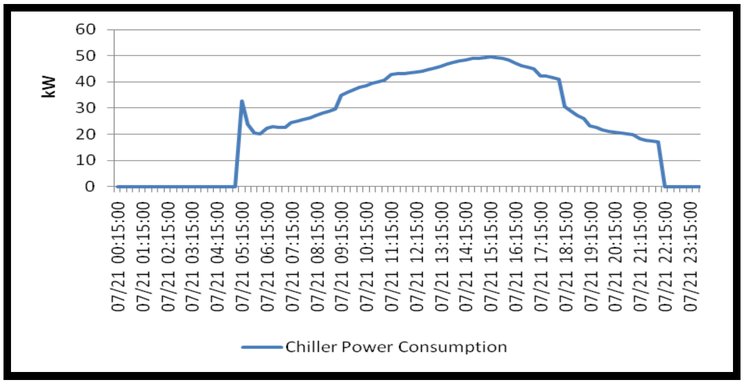

Figure 4-41 Miami Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design day, July 21st

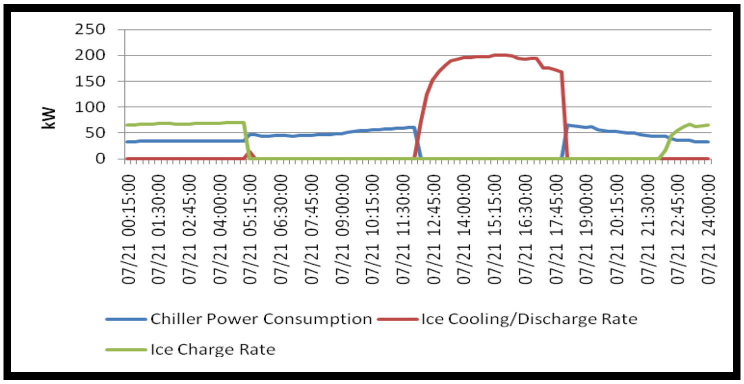

Figure 4-42 Miami Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

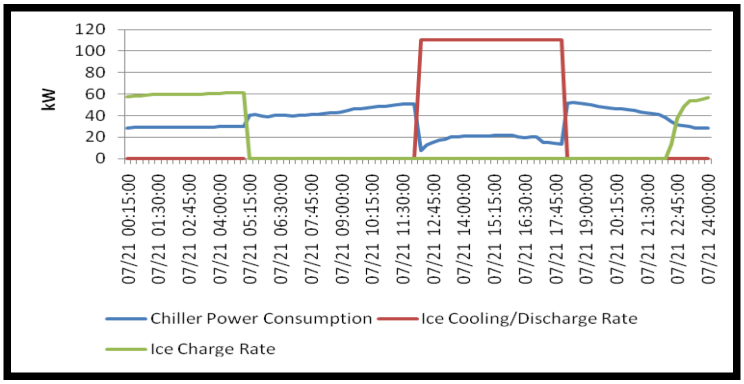

Figure 4-43 Miami Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

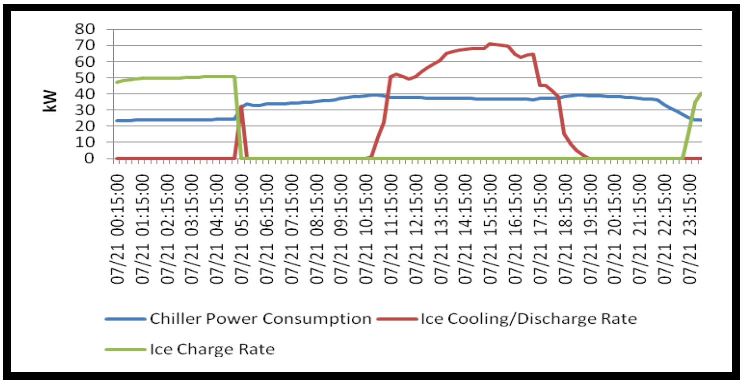

Figure 4-44 Miami Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-41 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-42 to 4-44 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-31 and 4-32 show chiller energy

consumption is higher for the ice storage systems than that for the non-storage systems. The chiller energy consumption for the storage priority system is slightly higher than the full storage system for the design day. This is due to the chiller operation during peak hours for the storage priority system when the ambient temperatures and RH both are high.

Table 4-31 Miami Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
244	586	Jun=14,502 July=15,941 Aug=15,087 Sep=14,641

Table 4-32 Miami Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
812	Jun=31,184 July=33,173 Aug=32,257 Sep=31,559	816	Jun=28,962 July=30,651 Aug=29,761 Sept=29,068	801	Jun=26,774 July=28,277 Aug=27,737 Sept=26,685

July and August are the hottest months in Miami with high chiller energy consumption for both the non-storage and the ice storage systems.

Table 4-33 Miami Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	277	0	110	223

Table 4-33 shows higher chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

B. Las Vegas

Figure 4-45 shows the cooling load profile for July 21st, the design day for Las Vegas.

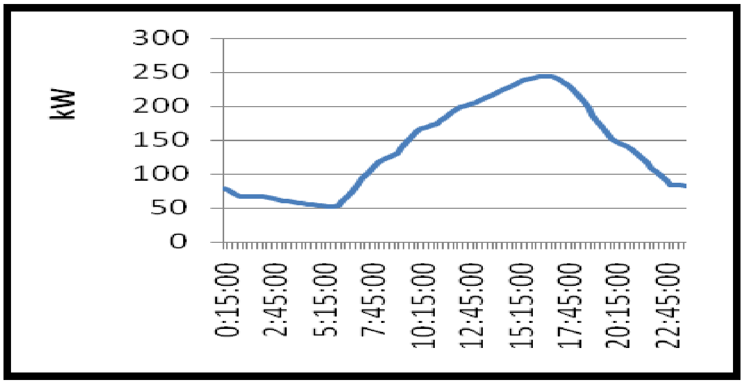

Figure 4-45 Las Vegas Medium-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-34.

Table 4-34 Las Vegas Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
3,658	239	13	185	6.5	120	2.5

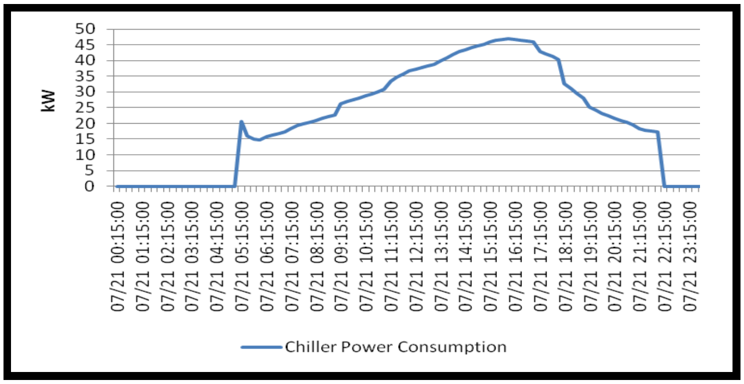

Figure 4-46 Las Vegas Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

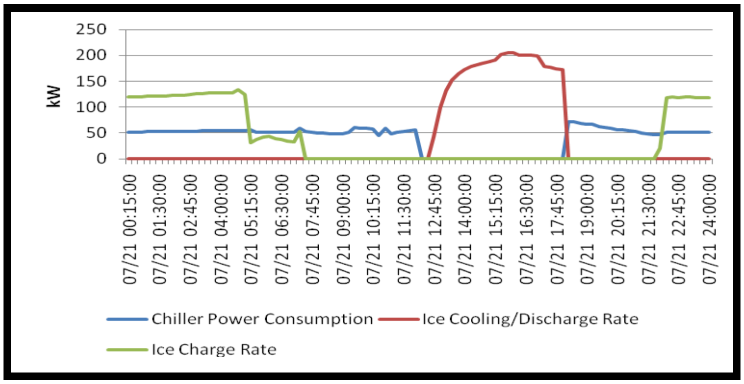

Figure 4-47 Las Vegas Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

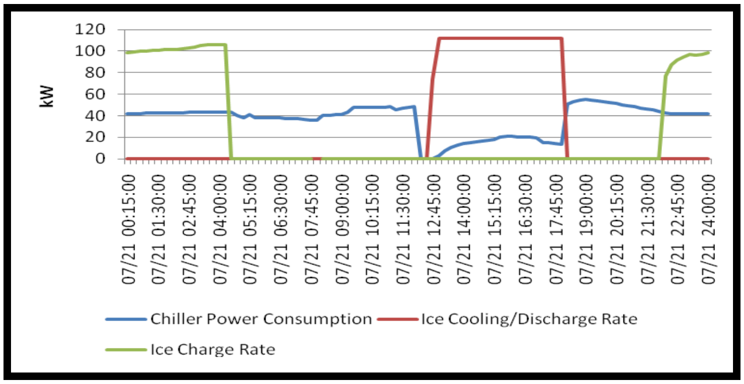

Figure 4-48 Las Vegas Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

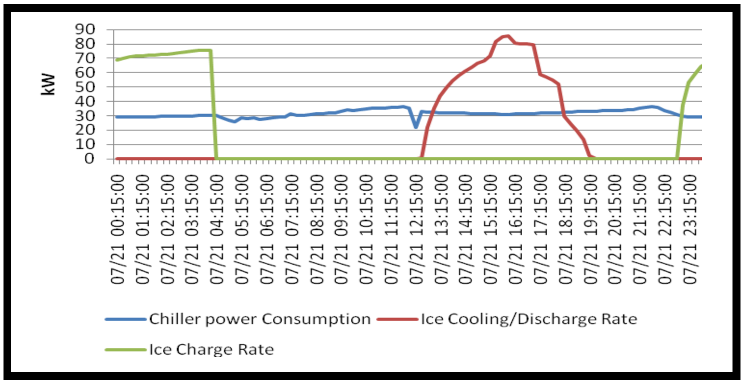

Figure 4-49 Las Vegas Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-46 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-47 to 4-49 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-35 and 4-36 show chiller energy consumption is higher for the ice storage systems than for the non-storage system.

Table 4-35 Las Vegas Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
232	517	Jun=14,243 July=17,058 Aug=15,925 Sep=12,166

Table 4-36 Las Vegas Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
974	Jun=31,819 July=35,429 Aug=34,948 Sep=31,006	878	Jun=29,384 July=32,170 Aug=31,427 Sept=28,302	754	Jun=24,494 July=26,918 Aug=26,595 Sept=23,734

Chiller energy consumption is higher for July and August, the hottest months in Las Vegas.

Table 4-37 Las Vegas Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	258	0	83	188

Table 4-37 shows higher chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

C. Baltimore

Figure 4-50 shows the cooling load profile for July 21st, the design day for Baltimore.

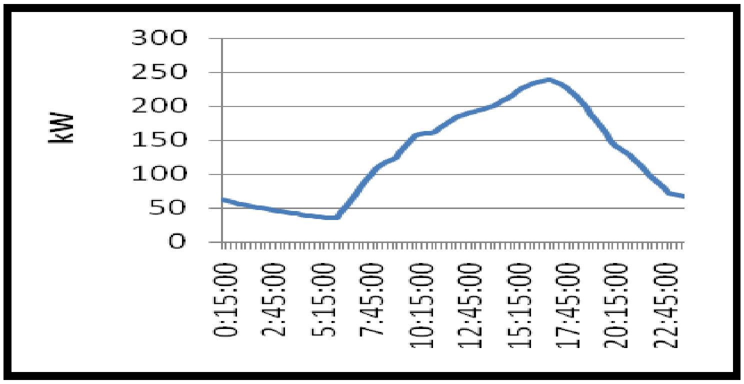

Figure 4-50 Baltimore Medium-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-38.

Table 4-38 Baltimore Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
3,388	221	12	171	6	115	2.5

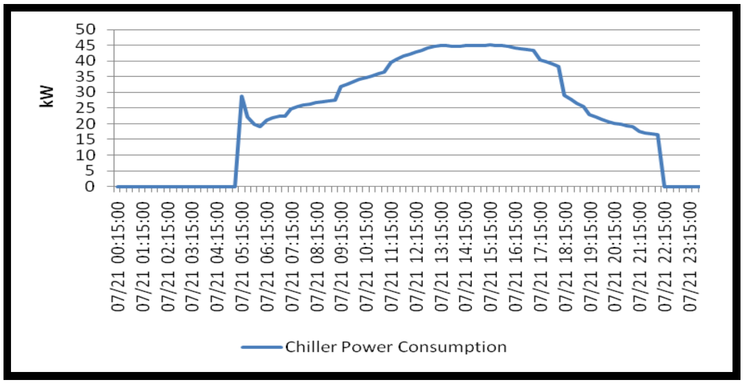

Figure 4-51 Baltimore Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

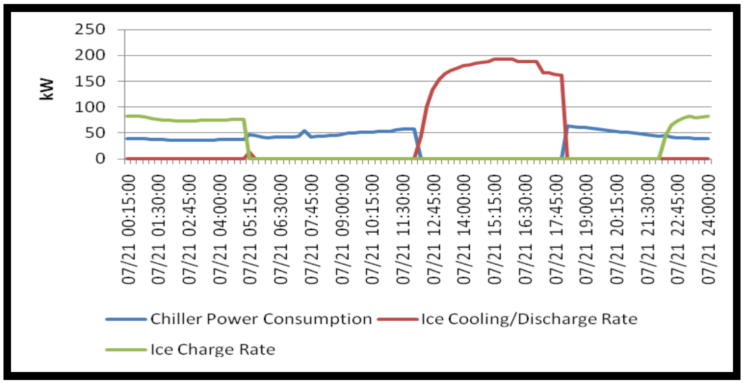

Figure 4-52 Baltimore Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

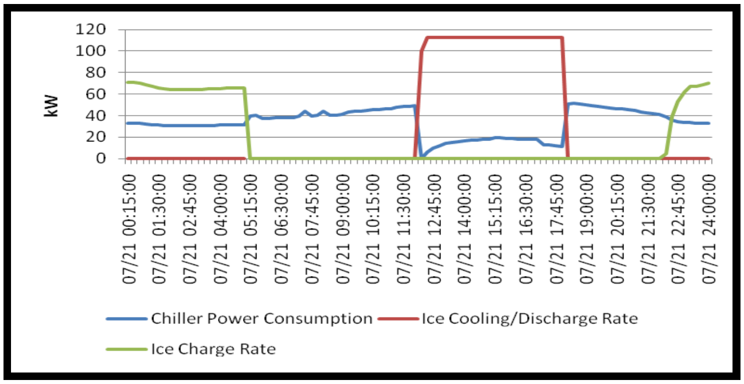

Figure 4-53 Baltimore Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

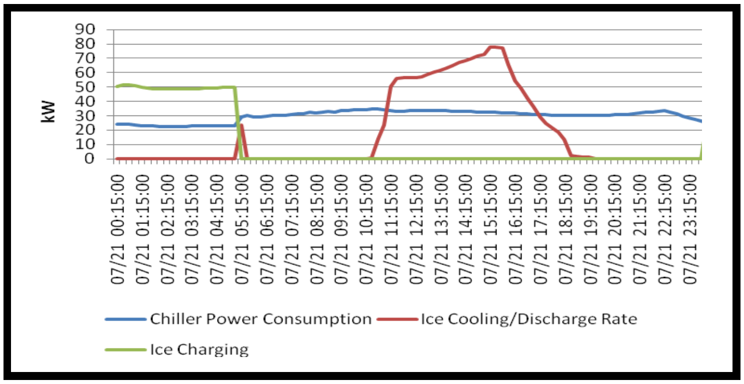

Figure 4-54 Baltimore Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-51 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-52 to 4-54 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-39 and 4-40 show chiller energy

consumption is higher for the ice storage systems than for the non-storage system.

Table 4-39 Baltimore Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
223	554	Jun=10,951 July=13,227 Aug=12,287 Sept=9,067

Table 4-40 Baltimore Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
821	Jun=28,024 July=31,354 Aug=31,119 Sept=24,243	799	Jun=25,754 July=28,881 Aug=28,091 Sept=22,170	716	Jun=21,985 July=24,985 Aug=24,618 Sept=19,078

July and August are the hottest months in Baltimore with high chiller energy consumption.

Table 4-41 Baltimore Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	261	0	89	194

Table 4-41 shows high chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

D. Seattle

Figure 4-55 shows the cooling load profile for Aug 21st, the design day for Seattle.

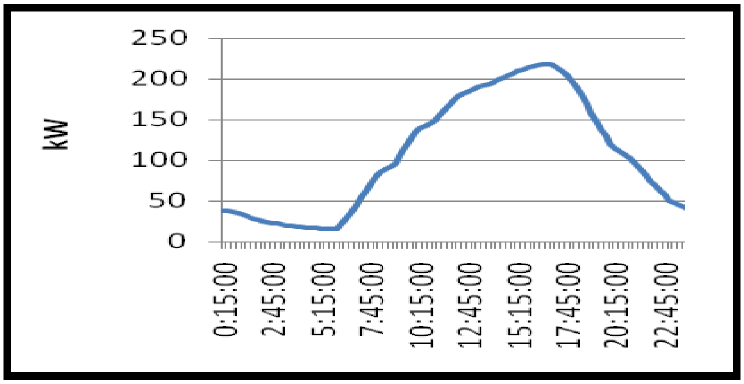

Figure 4-55 Seattle Medium-Sized Office Building: Cooling Load Profile on Design Day, Aug 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-42.

Table 4-42 Seattle Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
2,871	188	10.3	145	5	55	2

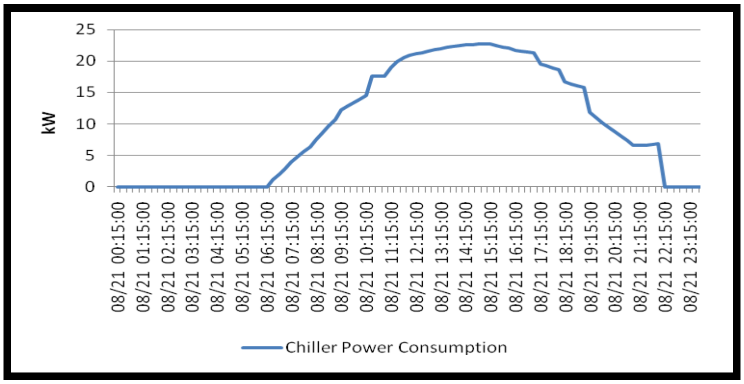

Figure 4-56 Seattle Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, Aug 21st

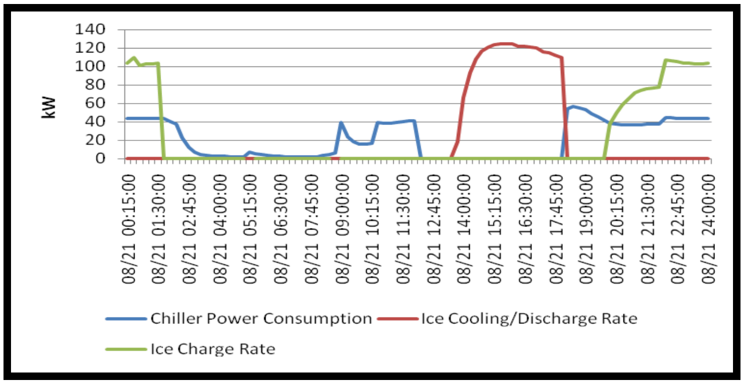

Figure 4-57 Seattle Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, Aug 21st

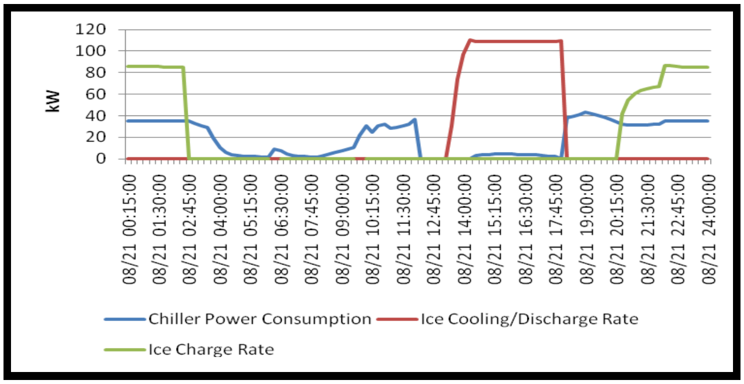

Figure 4-58 Seattle Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, Aug 21st

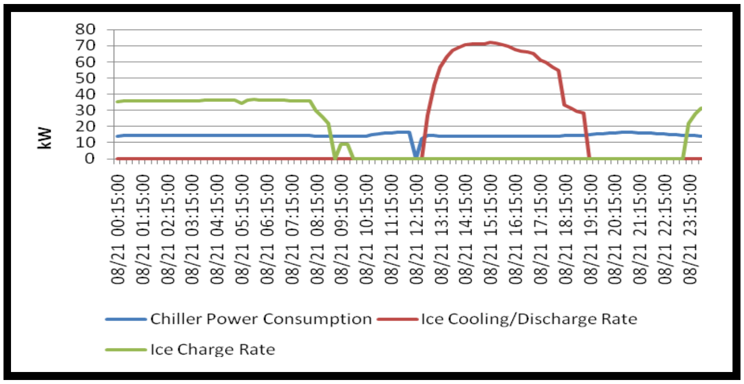

Figure 4-59 Seattle Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, Aug 21st

Figure 4-56 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-57 to 4-59 show the chiller energy consumption and ice charge and discharge rates for the storage systems. Tables 4-43 and 4-45 show chiller energy consumption is higher for the ice storage systems than for the non-storage system. The ice storage systems in Seattle have much higher chiller energy consumption than the non-storage system even in the cooler months since the air cooled system in Seattle with its mild climate operates more efficiently when the outside dry bulb temperatures are lower.

Table 4-43 Seattle Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
112	236	Jun=4,327 July=6,683 Aug=7,669 Sept=3,920

Table 4-44 Seattle Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
486	Jun=13,601 July=17,750 Aug=20,544 Sept=12,322	452	Jun=12,583 July=16,391 Aug=18,833 Sept=11,344	346	Jun=9,608 July=11,665 Aug=12,260 Sept=8,835

August is the warmest month in Seattle with high chiller energy consumption.

Table 4-45 Seattle Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	129	0	13	81

Table 4-45 shows high chiller energy consumption for the non-storage system during peak hours on the design day than the ice storage systems.

E. Chicago

Figure 4-60 shows the cooling load profile for July 21st, the design day for Chicago.

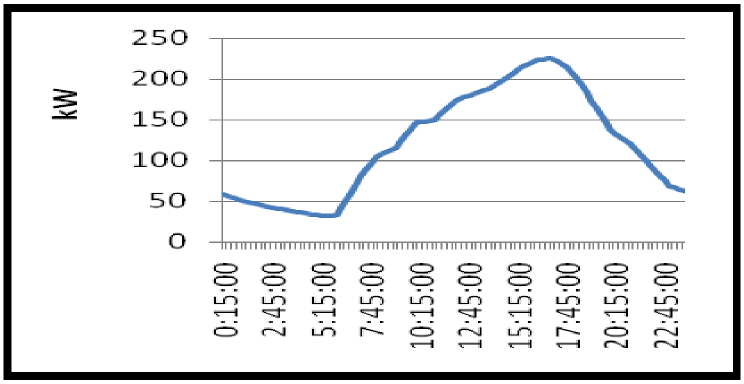

Figure 4-60 Chicago Medium-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of storage systems are summarized in Table 4-46.

Table 4-46 Chicago Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
3,189	208	11	161	6	100	2

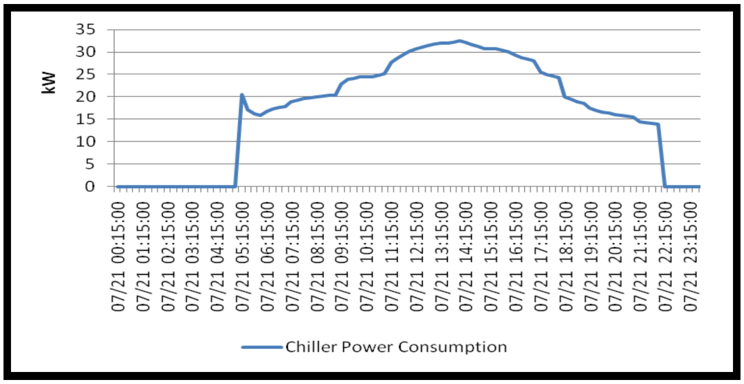

Figure 4-61 Chicago Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

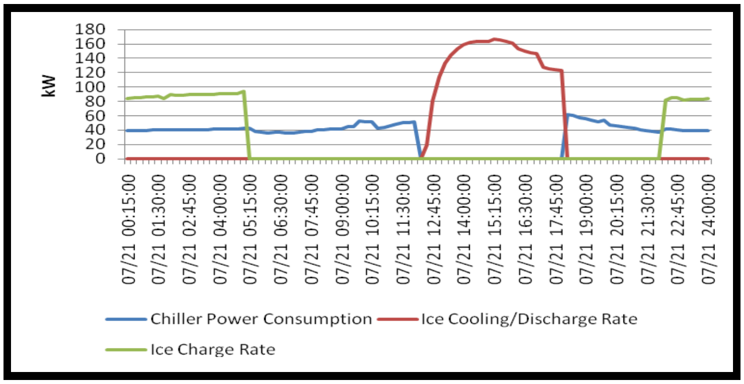

Figure 4-62 Chicago Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

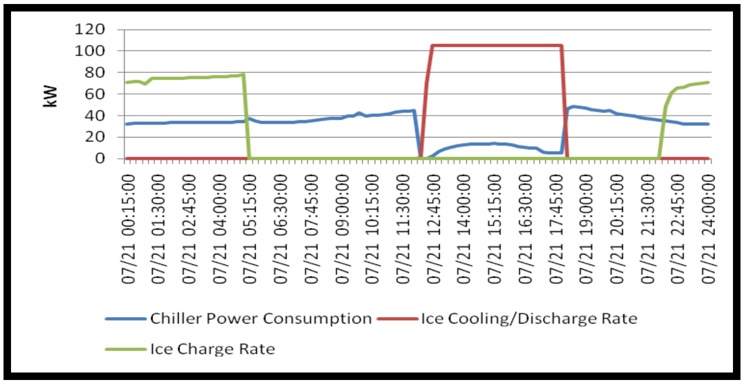

Figure 4-63 Chicago Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

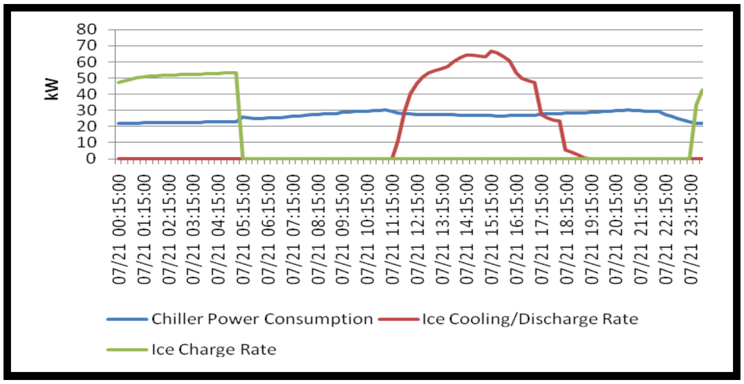

Figure 4-64 Chicago Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-61 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-62 to 4-64 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-47 and 4-48 show chiller energy

consumption is higher for the ice storage systems than for the non-storage system.

Table 4-47 Chicago Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
160	397	Jun=8,988 July=12,394 Aug=10,273 Sept=7,009

Table 4-48 Chicago Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
776	Jun=23,535 July=28,377 Aug=27,587 Sept=20,014	725	Jun=21,603 July=26,359 Aug=24,846 Sept=18,459	633	Jun=18,587 July=21,529 Aug=20,900 Sept=15,416

July and August are the warmest months in Chicago with high chiller energy consumption.

Table 4-49 Chicago Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	179	0	56	163

Table 4-49 shows high chiller energy consumption for the non-storage system during peak hours on the design day than that for the ice storage systems.

F. Helena

Figure 4-65 shows the cooling load profile for July 21st, the design day for Helena.

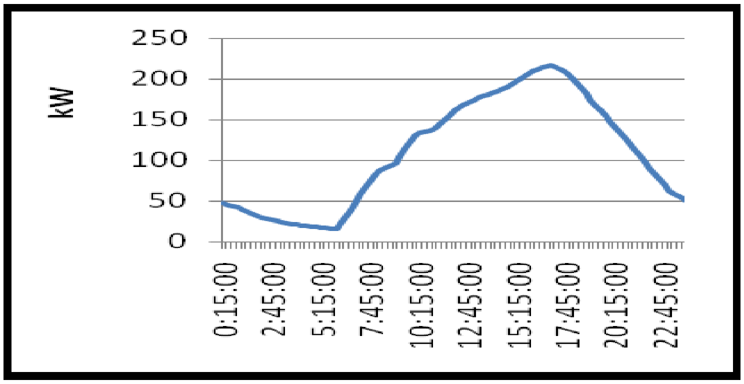

Figure 4-65 Helena Medium-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of ice storage systems are summarized in Table 4-50.

Table 4-50 Helena Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
2,924	191	10.5	148	5	100	2

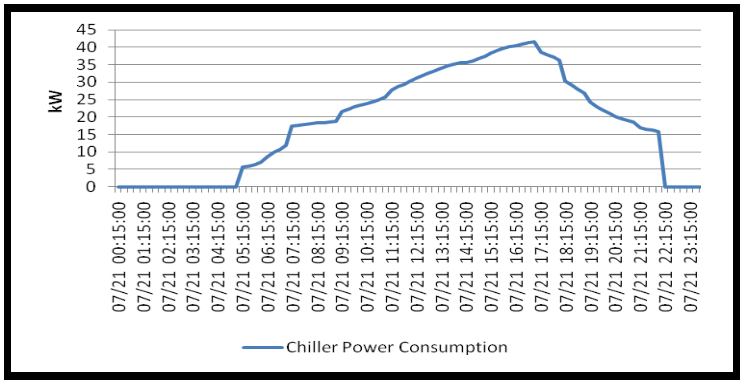

Figure 4-66 Helena Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

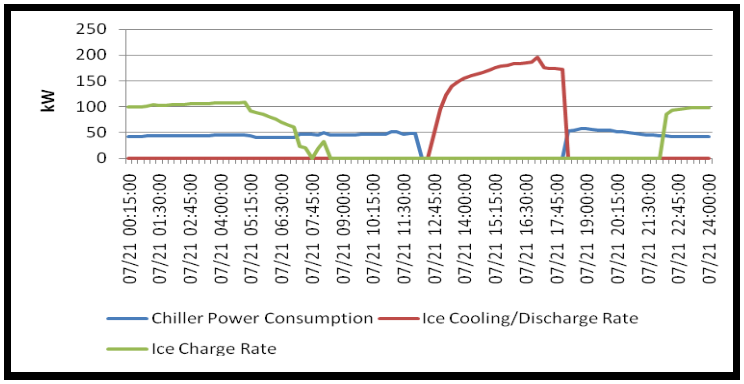

Figure 4-67 Helena Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

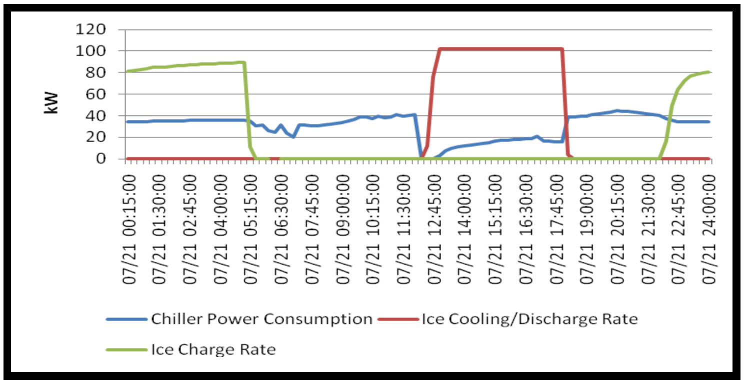

Figure 4-68 Helena Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

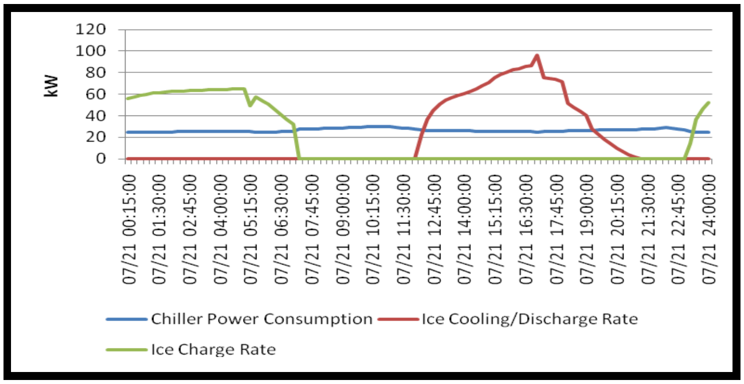

Figure 4-69 Helena Medium-Sized Office Building: Chiller Power Consumption and Ice Charge Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-66 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-67 to 4-69 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-51 and 4-52 show chiller energy consumption is higher for the ice storage systems than that for the non-storage system.

Table 4-51 Helena Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
205	438	Jun=5,936 July=8,786 Aug=6,976 Sept=4,001

Table 4-52 Helena Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
827	Jun=16,939	727	Jun=15,611	634	Jun=13,570
	July=23,662		July=21,482		July=18,518
	Aug=19,225		Aug=17,732		Aug=15,583
	Sept=13,584		Sept=12,563		Sept=10,763

July and August are the warmest months in Helena with high chiller energy consumption.

Table 4-53 Helena Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	222	0	78	154

Table 4-53 shows higher chiller energy consumption for the non-storage system during peak hours on the design day than that for the ice storage systems.

G. Duluth

Figure 4-70 shows the cooling load profile for July 21st, the design day for Duluth.

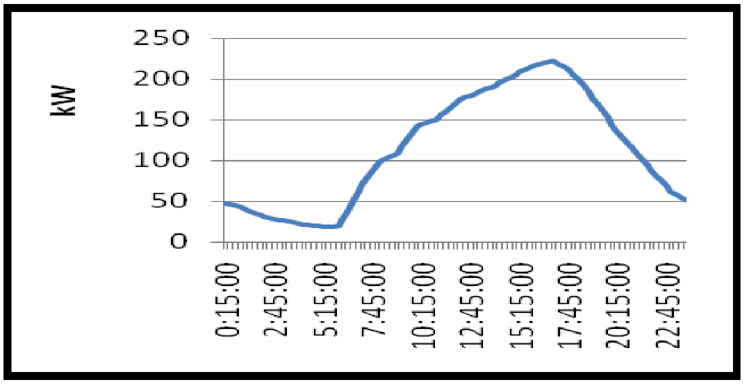

Figure 4- 70 Duluth Medium-Sized Office Building: Cooling Load Profile on Design Day, July 21st

The chiller and storage capacities for different types of storage systems are summarized in Table 4-54.

Table 4-54 Duluth Medium-Sized Office Building: Size of Ice Storage Systems

Total Integrated Cooling Load for Design Day	**Full Storage**		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
(kWh)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)	Chiller (kW)	Storage (GJ)
3,048	199	11	154	5	90	2

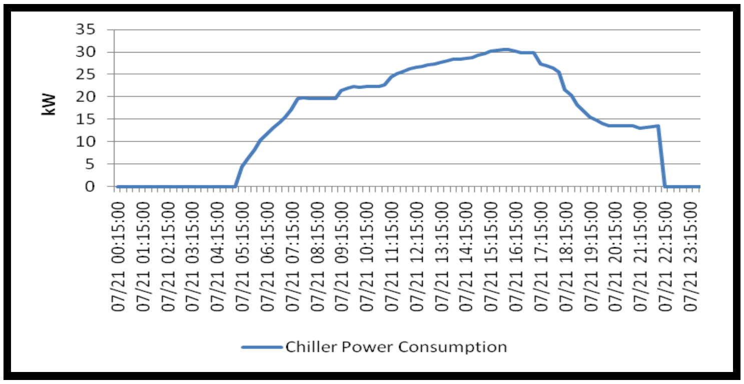

Figure 4-71 Duluth Medium-Sized Office Building: Chiller Power Consumption for Non Storage System on Design Day, July 21st

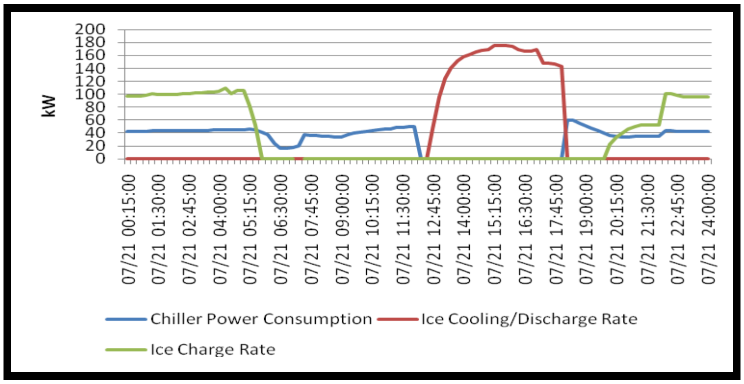

Figure 4-72 Duluth Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Full Storage System on Design Day, July 21st

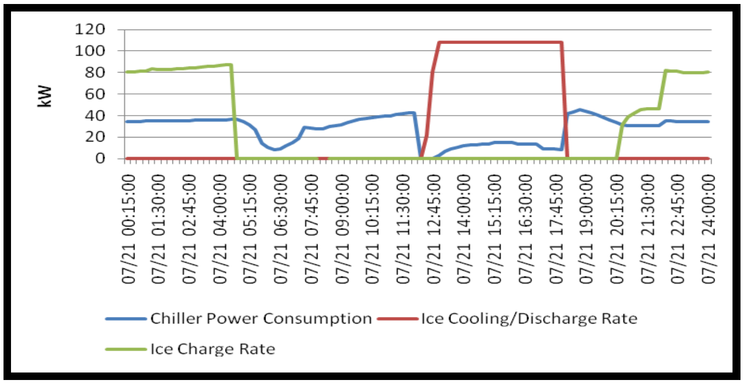

Figure 4-73 Duluth Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Storage Priority on Design Day, July 21st

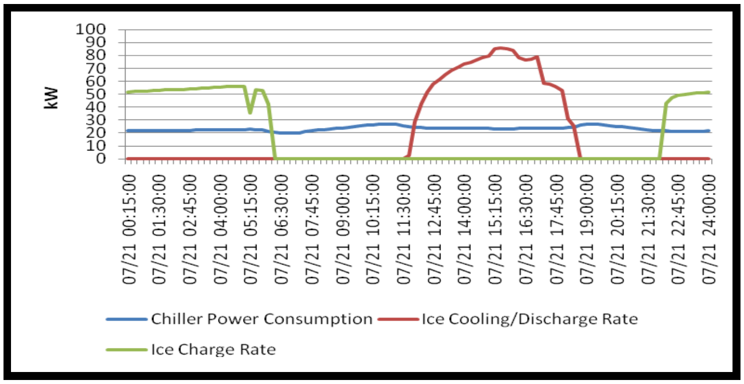

Figure 4-74 Duluth Medium-Sized Office Building: Chiller Power Consumption and Ice Charge/Discharge Rate for Chiller Priority on Design Day, July 21st

Figure 4-71 shows the chiller energy consumption for the non-storage system (air-cooled system). Figures 4-72 to 4-74 show the chiller energy consumption and ice charge and discharge rates for the ice storage systems. Tables 4-55 and 4-56 show chiller energy

consumption is higher for the ice storage systems than for the non-storage system.

Table 4-55 Duluth Medium-Sized Office Building: Chiller Energy Consumption for Non-Storage System

Non Storage System		
Chiller Size (kW)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
151	361	Jun=6,018 July=7,817 Aug=7,402 Sept=3,240

Table 4-56 Duluth Medium-Sized Office Building: Chiller Energy Consumption for Ice Storage Systems

Full Storage		**Partial Storage: Storage Priority**		**Partial Storage: Chiller Priority**	
Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)	Chiller Energy Consumption for Design Day (kWh)	Monthly Energy Consumption (kWh)
734	Jun=16,935 July=21,314 Aug=19,506 Sept=12,044	657	Jun=15,775 July=19,292 Aug=17,970 Sept=11,190	558	Jun=12,781 July=15,800 Aug=15,283 Sept=9,406

July and August are the warmest months in Duluth with high chiller energy consumption.

Table 4-57 Miami Medium-Sized Office Building: Design Day Chiller Energy Consumption during Peak Hours, Noon to 6 PM for Non-Storage and Ice Storage Systems

	Non-Storage	**Full Storage**	**Partial Storage: Storage Priority**	**Partial Storage: Chiller Priority**
Energy Consumption During Peak Hours (kWh)	171	0	61	142

Table 4-57 shows higher chiller energy consumption for the non-storage system on the design day than the ice storage systems.

Table 4-58 provides a comparison of the chiller energy consumption for the design day, and during peak hours, noon to 6 PM for the cities representing diverse climate zones.

Table 4-58 Medium-Sized Office Buildings: Design Day and Peak Hours Chiller Energy Consumption for Non-Storage and Ice Storage Systems in Diverse Climate Zones

	Non-Storage (kWh)	**Full Storage (kWh)**	**Partial Storage: Storage Priority (kWh)**	**Partial Storage: Chiller Priority (kWh)**
	Design Day (24 Hours) Chiller Energy Consumption			
Miami	586	812	816	801
Las Vegas	517	974	878	754
Baltimore	554	821	799	716
Seattle	236	486	452	346
Chicago	397	776	725	633
Helena	438	827	727	634
Duluth	361	734	657	558
	Peak Hours (Noon to 6 PM) Chiller Energy Consumption			
Miami	277	0	110	223
Las Vegas	258	0	83	188
Baltimore	261	0	89	194
Seattle	129	0	13	81
Chicago	179	0	56	163
Helena	222	0	78	154
Duluth	171	0	61	142

The full storage system in Miami, for example consumes 39% more chiller energy than the air-cooled system but eliminates the chiller operation during peak-hours. The storage priority system in Miami, shows slightly higher chiller energy consumption than that of the full storage system. The chiller priority system for the cities shows considerable peak demand shift when compared with conventional air-cooled systems unlike large-sized office buildings where peak demand shift was insignificant. It is also observed that for Seattle, chiller priority achieves more peak energy savings, 37% as compared to the air-cooled system, than in the other climate zones. Chiller priority in Helena achieves the next highest peak energy savings, 31%. This is followed by Las Vegas and Baltimore at 27% and 26% respectively. Figure 4-75 compares the chiller energy consumption for non-storage system for the selected cities. Figure 3-2 and Table 3-2 have been referred for average temperatures and RH.

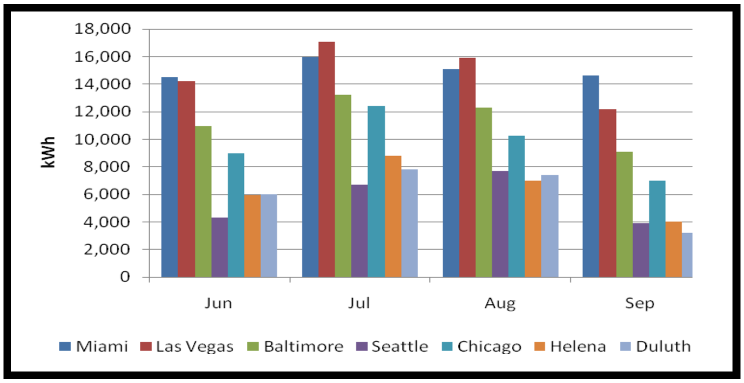

Figure 4-75 Medium-Sized Office Building Chiller Energy Consumption for Non-Storage System in Diverse Climate Zones

Figure 4-75 shows higher chiller energy consumption for Las Vegas in July and August. In July and August Las Vegas has extremely high day temperatures causing more chiller energy consumption for the air cooled non-storage system since the high outside dry bulb temperatures make chiller operation inefficient. In June and September Las Vegas has comparatively lower temperatures, and Miami with its less variation in day and evening temperatures has higher chiller energy consumption. Baltimore has higher summer temperatures than Seattle, Chicago, Helena and Duluth as a result the chiller energy consumption is also higher. Chicago temperatures follow next resulting in next higher chiller energy consumption. Seattle, Helena and Duluth with their mild summer climate have comparable chiller energy consumptions. Except for in June and July Seattle has lower temperatures than Helena and Duluth resulting in lower chiller energy consumption.

Figures 4-76 to 4-78 compare the chiller energy consumption for various ice storage systems.

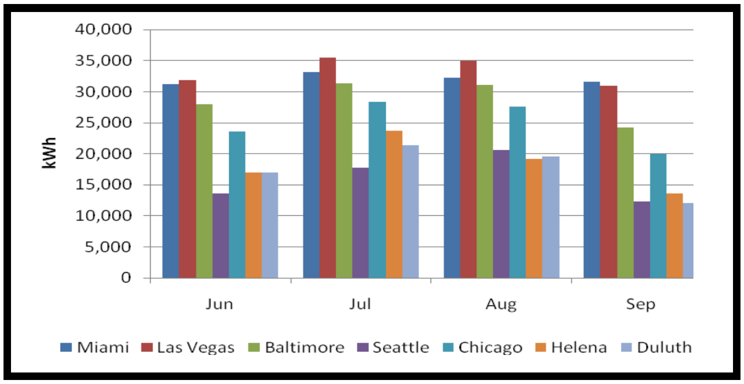

Figure 4-76 Medium-Sized Office Building Chiller Energy Consumption for Full Storage in Diverse Climate Zones

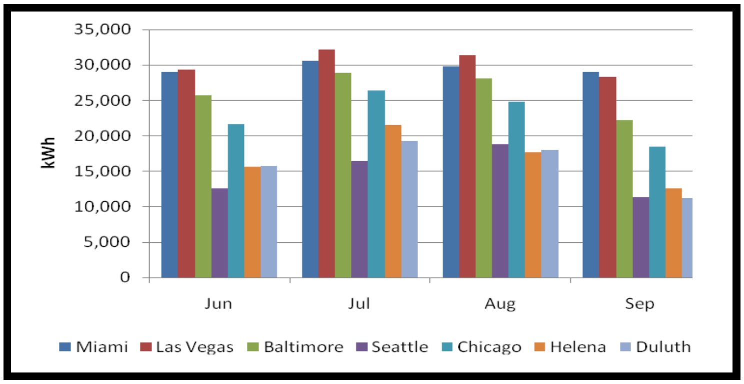

Figure 4-77 Medium-Sized Office Building Chiller Energy Consumption for Partial Storage: Storage Priority in Diverse Climate Zones

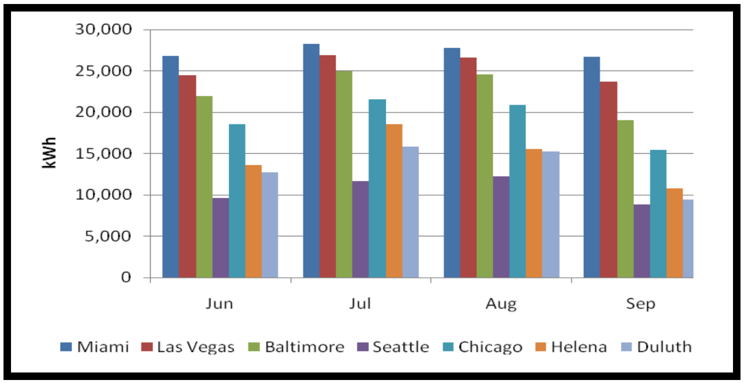

Figure 4-78 Medium-Sized Office Building Chiller Energy Consumption for Partial Storage: Chiller Priority in Diverse Climate Zones

The ice storage systems have water-cooled condensers and face the issue of lower COP with high RH and ambient temperatures. Miami has high RH, which reduces the evaporative cooling of condenser water, the high RH may also cause trapment of moisture in the fiberglass insulation. On the other hand Las Vegas has high outside temperatures causing more heat transfer through building envelope and raising condenser water temperatures. Due to these factors both Miami and Las Vegas have comparable chiller energy consumption. For full storage and storage priority, chiller energy consumption is slightly higher for Las Vegas in July and August when the temperatures are very high there. However for chiller priority the energy consumption for Miami is higher during these months due to continuous chiller operation during day-time when the outside RH is high. Baltimore and Chicago with their high temperatures and RH follow next. August is the warmest month in Seattle and in August Seattle's night-time temperatures are slightly higher than Duluth and Helena, therefore the chiller energy consumption is higher due to more energy needed for ice making. For the same month, chiller priority consumes less energy than Helena and Duluth since a small ice tank has to be charged during night. Helena and Duluth have comparable chiller energy consumption with Helena having slightly higher energy consumption in July due to higher temperatures.

5. CONCLUSIONS AND CONTRIBUTIONS

The thesis models and simulates large and medium-sized office buildings in diverse climate zones with conventional non-storage and ice storage systems. The non-storage systems include hydronic cooling systems for large-sized office buildings and air-cooled systems for medium-sized office buildings. The operating and control strategies for the ice storage systems analyzed include full storage and partial storage with storage priority and chiller priority. The peak energy savings for the design day as a result of ice storage systems have been investigated. Also the monthly chiller energy consumption during a summer season for both the conventional non-storage and ice storage systems has been analyzed. The results indicate that the ice storage systems have higher chiller energy consumption than the conventional non-storage systems due to the day and night chiller operation. For example, the design day chiller energy consumption of the hydronic system in the large-sized office building in Miami is 4,267 kWh. Whereas for the full storage, storage priority and chiller priority systems in the same building the design day chiller energy consumptions are 7,391 kWh, 7,350 kWh and 6,350 kWh respectively. Similarly, the design day chiller energy consumption of the air-cooled system in a medium-sized office building in Miami is 586 kWh. For the full storage, storage priority and chiller priority systems in the same building the design day chiller energy consumptions are 812 kWh, 816 kWh and 801 kWh respectively. By discharging ice storage during the peak hours, the ice storage systems are able to achieve peak energy savings by reducing or even eliminating the chiller operation. This can be seen from Figures 4-3 to 4-5 for large-sized office buildings and Figures 4-42 to 4-44 for medium-sized office buildings in Miami; showing the chiller power consumption for ice storage systems. The chiller is nonoperational during peak hours for the full storage systems. For partial storage systems the chiller power consumption is reduced. The chiller energy consumption for the ice storage systems depends upon climatic conditions. The climate zones with high summer temperatures and RH not only increase the building cooling load but also decrease the cooling of condenser water thereby increasing the chiller energy consumption. For example, Miami with its high temperatures and RH in a summer season shows high chiller energy consumption for both large and medium-sized office buildings. Similarly, Las

Vegas has extremely high temperatures in the summer season and it too shows high chiller energy consumption for both large and medium-sized office buildings. On the contrary the climate zones with less extreme summers have lower chiller energy consumption due to lower building cooling loads and more cooling of condenser water. For example, Seattle, Helena and Duluth have mild summer seasons and have low chiller energy consumptions for both large and medium-sized office buildings. The analysis provides guidelines for utilities and building owners to determine potential benefits of ice storage systems for different climate zones and ice storage operating strategies.

The primary contribution of this thesis research work is the analysis of the chiller energy consumption and peak energy savings as a result of ice storage systems in diverse climate zones for large and medium-sized office buildings.

Further conclusions and contributions as a result of the analysis performed here include:

1) Verification of the results demonstrated by [17] for a small-sized office building in hot and dry climate zone. The results showed increased chiller energy consumption for partial ice storage systems (storage priority and chiller priority) than conventional non-storage cooling system for the design day. The ice storage systems were also able to achieve peak energy savings.

2) Validation of the charging/discharging processes for internal melt ice-on-coil systems with charging/discharging principles demonstrated by [25].

3) Extends the work by [11] whereby chiller energy consumption of ice storage systems (full storage and chiller priority) has been compared with conventional air-cooled systems for a medium-sized office building in hot/humid climate zone. The ice storage systems had air-cooled condensers. The thesis compares the chiller energy consumption of ice storage systems with conventional hydronic and air-cooled systems in large and medium-sized office buildings respectively. Also the thesis models these large and medium-sized office buildings in diverse climate zones.

4) Authors in [35] evaluated the energy use intensities for the hydronic cooling system in large-sized office buildings for different climate zones. The results showed higher

intensities for hot climate zones. The thesis results also show higher monthly and design day chiller energy consumption for hydronic systems and air-cooled systems in hot climate zones.

5) Higher chiller COP has been demonstrated by [27] for an internal melt ice-on-coil system during direct cooling than ice making operation. The system had a chiller downstream of ice tank. The ice storage system analyzed in this research had a chiller upstream of ice tank. The results indicate increased chiller COP when providing direct cooling as compared to ice making operation for this system.

6. FUTURE WORK

Cost benefit analysis for ice storage systems is beyond the scope of this thesis. However the results from this thesis will provide the necessary energy consumption savings information required for such cost-benefit analysis.

References

1. *http://poet.lbl.gov/drrc/tools-drqat-download.html* [cited 2011 May].
2. Valenta, P., in The Daily Energy Report.
3. Beck, R.W., Ice Bear Energy Storage System Electric Utility Modeling Guide 2011.
4. Dincer, I. and M.A. Rosen, Thermal Energy Storage Systems and Applications. 2011, John Wiley & Sons, Ltd
5. Charles E. Dorgan, J.S.E., Design Guide for Cool Thermal Storage. 1993: ASHRAE.
6. CHAPTER 50: THERMAL STORAGE. 2008, American Society of Heating, Refrigerating & Air-Conditioning Engineers, Inc. p. 50.1.
7. Laybourn, D.R. and V.A. Baclawski, The Benefits of Thermal Energy Storage for Cooling Commercial Buildings. Power Apparatus and Systems, IEEE Transactions on, 1985. **PAS-104**(9): p. 2356-2360.
8. Thirrvrsin, P., J. Sinthusonthichrt, and S. Potivejkul, Design and Construction of Mini Ice Storage Air Conditioning System, in IEEE TENCON. 1999.
9. Farahani, M.E.S. and N. Saeidi. Case Study of Design and Implementation of a Thermal Energy Storage System. in Power and Energy Conference, 2006. PECon '06. IEEE International. 2006.
10. H. Akbari, O.S., Case Studies of Thermal Energy Storage (TES) Systems: Evaluation and Verification of System Performance. 1992, Lawrence Berkeley Laboratory, University of California, Energy and Environment Division, Berkeley, CA.
11. Sohn, C.W., Field Performance of an Ice Hravester Storage Cooling System. ASHRAE Transactions, 1991. **97**(2): p. 1187-1193.
12. Chatchawan Chaichana, W.W.S.C., Lu Aye, An Ice Thermal Storage Computer Model. Applied Thermal Engineering, 2001. **21**(17): p. 1769-1778.
13. Leight, S.P.a.J.S.E., Case Study of an Ice storage System With Cold Air Distribution and Heat Recovery. 1993, Palo Alto,CA:Electric Power Research Institute.
14. K.H. Drees, J.E.B., Development and evaluation of a rule-based control strategy for ice storage systems. International Journal of HVAC&R Research, 1996. **2**(4): p. 312-336.
15. G.P. Henze, M.K., M. Brandemuehl, A simulation environment for the analysis of ice storage controls. International Journal of HVAC&R Research, 1997. **3**(2): p. 128-148.
16. D. King, R.P., Description of a steady-state cooling plant model developed for use in evaluating optimal control of ice thermal energy storage systems. ASHRAE Transactions 1998. **104**(1): p. 42-54.
17. D.J. King, R.A.P., Description of a steady-state cooling plant model developed for use in evaluating optimal control of ice thermal energy storage systems. ASHRAE Transactions, 1998. **104** (1A): p. 42-53.
18. Ihm, P., M. Krarti, and G.P. Henze, Development of a thermal energy storage model for EnergyPlus. Energy & Buildings, 2004. **36**(8): p. 807-814.
19. Hajiah, A.E.H., Development and Implementation of an Optimal Controller of a Central Cooling Plant Using Ice Storage System and Building Thermal Mass, in Department of Civil, Environmental and Architectural Engineering. 2000, University of Colorado: Boulder.
20. Huei-Jiunn Chen , D.W.P.W., Sih-Li Chen, Optimization of an Ice-Storage Air Conditioning System Using Dynamic Programming Method. Applied Thermal Engineering,

2005. **25**(2-3): p. 461–472.

21. Moncef Krarti, M.J.B.a.G.P.H., Evaluation of Optimal Control for Ice Storage Systems. 1995, ASHRAE.

22. Massie, D.D., Optimization of a building's cooling plant for operating cost and energy use. International Journal of Thermal Sciences, 2002. **41**(12): p. 1121-1129.

23. Henze, G.P.K., Moncef;Brandemuehl, Michael J., Guidelines for Improved Performance of Ice Storage Systems. Energy & Buildings, 2003. **35**(2): p. p111-p127.

24. M. Kintner-Meyer, A.F.E., Cost optimal analysis and load shifting potentials of cold storage equipment. ASHRAE Transactions, 1995. **101**(2): p. 539-548.

25. Stovall, T.K., CALMAC Ice Storage Test Report, . 1991, Oak Ridge,TN:Oak Ridge National Laboratory.

26. Zhu, Y. and Y. Zhang, Modeling of thermal processes for internal melt ice-on-coil tank including ice-water density difference. Energy and Buildings, 2001. **33**(4): p. 363-370.

27. Sohn, C.W., G.L.Cler and R.J.Kedl, Performance of an ice-in-tank diurnal ice storage cooling system at Fort Stewart,GA. 1990, USA CERL.

28. Leight, S.P.a.J.S.E., Case study of an ice storage system with cold air distribution and heat recovery. 1993, Palo Alto, CA:Electric Power Research Institute.

29. Braun, J.E., Load Control Using Building Thermal Mass. Journal of Solar Energy Engineering, 2003. **125**: p. 292-301.

30. PG&E, Thermal Energy Storage Strategies for Commercial HVAC Systems. 1997.

31. Source Energy and Environmental Impacts of Thermal Energy Storage. 1996, Calfornia Energy Commission.

32. *http://www.hku.hk/mech/msc-courses/MEBS6008/index.html* [cited 2011 May].

33. Naguib, R., Hybrid Ice thermal Energy Storage:All-in-one Innovative New System Concept. Air Conditioning and Refrigeration Journal, 2006.

34. CALMAC, Evapco Ice Coils : Quality Coils Designed for Large Thermal Storage Systems.

35. PNNL, Thermal Energy Storage for Space Cooling. 2000, FEMP DOE.

36. Michael Deru, K.F., Daniel Studer, Kyle Benne, Brent Griffith, Paul Torcellini,Bing Liu, Mark Halverson, Dave Winiarski, Michael Rosenberg,Mehry Yazdanian,Joe Huang and Drury Crawley, U.S. Department of Energy Commercial Reference Building Models of the National Building Stock. 2011, NREL.

37. Matthew Leach, C.L., Adam Hirsch, Shanti Pless, and Paul Torcellini, Technical Support Document: Strategies for 50% Energy Savings in Large Office Buildings. 2010, NREL.

38.*http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=4_north_and_central_america_wmo_region_4/country=1_usa/cname=USA*. 17 March 2011 [cited 2011 01 May].

39. *http://www.rssweather.com/climate/*. [cited 2011 May].

40. *http://www.ncdc.noaa.gov/ol/climate/climateproducts.html*. 06 Jan 2010 [cited 2011 May].

41. *http://www.eere.energy.gov/*. 09/30/2010 [cited 2011 07/01].

42. BA Thornton, W.W., MD Lane,MI Rosenberg,B Liu, Technical Support Document: 50% Energy Savings Design Technology Packages for Medium Office Buildings. 2009, PNNL.

43. Detlef Westphalen, S.K., Energy Consumption Characteristics of Commercial Building

HVAC Systems Volume II: Thermal Distribution, Auxiliary Equipment, and Ventilation. 1999, Arthur D. Little, Inc.

44. Resources, E.D., Chilled Water Plant Design Guide. 2009.

45. Herbert, I., et al., Air-Conditioning and Refrigeration, in The CRC Handbook of Mechanical Engineering, Second Edition. 2004, CRC Press.

46. Bhatia, A., Heat Rejection Options in HVAC Systems, Continuing Education and Development, Inc.

47. *http://www.ecofoil.com/Applications/Metal-Building-Insulation* [cited 2011 July]

Appendix A

The following schedules are based on [37]

AA Lighting Schedule

Lighting (Fraction)			
Hour	Weekdays	Saturday	Sunday, Holiday
1	0.05	0.05	0.05
2	0.05	0.05	0.05
3	0.05	0.05	0.05
4	0.05	0.05	0.05
5	0.05	0.05	0.05
6	0.05	0.05	0.05
7	0.40	0.05	0.05
8	0.75	0.4	0.05
9	0.75	0.75	0.4
10	0.90	0.75	0.4
11	0.90	0.75	0.4
12	0.90	0.75	0.4
13	0.90	0.75	0.4
14	0.90	0.75	0.4
15	0.90	0.75	0.4
16	0.90	0.4	0.4
17	0.90	0.4	0.4
18	0.90	0.4	0.4
19	0.75	0.4	0.05
20	0.75	0.05	0.05
21	0.75	0.05	0.05
22	0.40	0.05	0.05
23	0.05	0.05	0.05
24	0.05	0.05	0.05

AB Electric Plug Loads Schedule

Electric Plug Loads (Fraction)			
Hour	Weekdays	Saturday	Sunday, Holiday
1	0.20	0.15	0.15
2	0.20	0.15	0.15
3	0.20	0.15	0.15
4	0.20	0.15	0.15
5	0.20	0.15	0.15
6	0.20	0.15	0.15
7	0.40	0.15	0.15
8	0.40	0.35	0.15
9	0.40	0.35	0.35
10	0.70	0.35	0.35
11	0.70	0.35	0.35
12	0.90	0.35	0.35
13	0.90	0.35	0.35
14	0.90	0.35	0.35
15	0.90	0.35	0.35
16	0.90	0.35	0.35
17	0.90	0.35	0.35
18	0.70	0.35	0.35
19	0.40	0.35	0.15
20	0.20	0.15	0.15
21	0.20	0.15	0.15
22	0.20	0.15	0.15
23	0.20	0.15	0.15
24	0.20	0.15	0.15

AC Occupancy Schedule

Occupancy (Fraction)			
Hour	Weekdays	Saturday	Sunday, Holiday
1	0.00	0	0
2	0.00	0	0
3	0.00	0	0
4	0.00	0	0
5	0.00	0	0
6	0.00	0	0
7	0.05	0	0
8	0.15	0.05	0
9	0.20	0.2	0.05
10	0.50	0.2	0.05
11	0.50	0.2	0.05
12	0.70	0.2	0.05
13	0.70	0.1	0.05
14	0.70	0.1	0.05
15	0.70	0.1	0.05
16	0.80	0.05	0.05
17	0.70	0.05	0.05
18	0.30	0.05	0.05
19	0.10	0.05	0
20	0.05	0	0
21	0.05	0	0
22	0.00	0	0
23	0.00	0	0
24	0.00	0	0

AD HVAC Schedule

HVAC system on/off				Cooling set point (ºF)		
Hour	Weekdays	Saturday	Sunday, Holiday	Weekdays	Saturday	Sunday, Holiday
1	0.00	0	0	87.08	87.08	87.08
2	0.00	0	0	87.08	87.08	87.08
3	0.00	0	0	87.08	87.08	87.08
4	0.00	0	0	87.08	87.08	87.08
5	0.00	0	0	87.08	87.08	87.08
6	1.00	0	0	75.2	87.08	87.08
7	1.00	1	0	75.2	75.2	87.08
8	1.00	1	1	75.2	75.2	75.2
9	1.00	1	1	75.2	75.2	75.2
10	1.00	1	1	75.2	75.2	75.2
11	1.00	1	1	75.2	75.2	75.2
12	1.00	1	1	75.2	75.2	75.2
13	1.00	1	1	75.2	75.2	75.2
14	1.00	1	1	75.2	75.2	75.2
15	1.00	1	1	75.2	75.2	75.2
16	1.00	1	1	75.2	75.2	75.2
17	1.00	1	1	75.2	75.2	75.2
18	1.00	1	1	75.2	75.2	75.2
19	1.00	1	0	75.2	75.2	87.08
20	1.00	0	0	75.2	87.08	87.08
21	1.00	0	0	75.2	87.08	87.08
22	1.00	0	0	75.2	87.08	87.08
23	0.00	0	0	87.08	87.08	87.08
24	0.00	0	0	87.08	87.08	87.08