EVALUATION OF THE ECONOMIC BENEFITS OF SHIFTING AIR CONDITIONING LOADS FROM EVENING AND DAY PEAKS TO OFF PEAK HOURS

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149290U

Degree of Master of Science

Department of Electrical Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISORS

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(Eng. W. D. A. S. Wijayapala)	

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Signature of the supervisor	Date
(Eng. Chandana N. Dalugoda)	

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ABSTRACT

With the development of industries and changes in living standards of the society, demand for electricity is rapidly increasing in every year. In order to maintain the demand supply balance and to provide uninterrupted supply, utility has to supply the electricity demand in the most economical way. Building new power plants is not always the most economical solution. The trend now, is towards reducing and controlling the demand through Demand Side Management (DSM) techniques which is almost always an economical and environment-friendly solution.

In this thesis, Heating, Ventilation and Air Conditioning (HVAC) system of Cinnamon Lakeside Hotel is analyzed to identify the potential DSM options that can be implemented. Thermal Energy Storage (TES) was selected as the DSM option to store cooling load in off-peak hours of the day and use it in peak and day hours of the day. Technical viability and potential saving that can be achieved through TES in hotel sector of Sri Lanka is further analyzed.

Benefits of Thermal Energy Storage systems to the industry and to the utility is separately analyzed in this study.

The conclusion of the thesis is that Thermal Energy Storage technology is a viable DSM method for the hotel industry in Sri Lanka. It is the responsibility of the Government and the Utility to promote DSM methods to its customers and motivate them to invest.

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LIST OF ABBREVIATIONS

Abbreviation	Description
BST	Bulk Supply Tariff
CEB	Ceylon Electricity Board
COP	Coefficient of Performance
CWS	Chilled Water Storage
DSM	Demand Side Management
FOM	Figure of Merit
GP	General Purpose
GV	Government
H	Hotel
HVAC	Heating Ventilation and Air Conditioning
I	Industrial
IPP	Independent Power Producer
IRR	Internal Rate of Return
kVA	kilovolt Ampere
kW_e	kilowatt (electrical)
kWh_e	kilowatt hour (electrical)
kWh_R	kilowatt hour (cooling)
MW	Megawatt
PUCSL	Public Utilities Commission of Sri Lanka
TR	Ton of Refrigeration
TRh	Ton of Refrigeration hour
SPP	Small Power Producer
TES	Thermal Energy Storage
TOU	Time of Use

1. INTRODUCTION

1.1. Background

Thermal comfort is a main factor in modern day building designs. Air conditioners are generally used to provide thermal comfort inside buildings. Due to the changes in living standards of the urban population, the use of air conditioning is increasing around the world and hence, the demand of electricity is also increasing every year. Thus, energy consumption for providing thermal comfort in buildings is also increasing and contributing to about 40% of the global energy consumption. The use of conventional fossil fuels for electricity generation is the main cause of CO_2 emission into the atmosphere. This CO_2 emission in the atmosphere is the major contributor of global warming.

Population and income growth are the two most powerful driving forces behind the demand for energy. The next 20 years is likely to see continued global integration and rapid growth of low and medium income economies. Hence, due to the rapid change in life style and living standards of people of developing countries lead the growing demand of energy consumption. Promoting energy efficiency and conservation in buildings is therefore, becoming one of the major issues of concern to governments and societies today. To meet the peak demand either peaking power stations have to be set up or energy has to be stored during off peak hours. The first option would lead to a relatively higher cost of generation and higher emissions. The latter option would help towards flattening the demand curve, increase the plant factor of the power plants, and lower the generation costs and reduce emissions. Such variation leads to a differential pricing system for peak and off peak periods of energy use. Better Energy Demand Side Management (DSM) and significant economic benefit can be achieved if some of the peak load could be shifted to the off peak period.

HVAC systems in industry, commercial and air conditioning in residential buildings is the largest single contributor to electrical peak demand especially during daytime. This requires the electric suppliers to bring additional, more costly generation plants on line to handle this increased demand.

During recent years, research aimed for the development of technologies that can offer reduction in energy consumption, peak electrical demand and energy costs without affecting the level of thermal comfort. In this context, Thermal Energy Storage (TES) systems can play an important role as they provide great potential for improved energy efficiency, conservation and to reduce peak electrical load. Hence, cold TES technologies can provide a vital link between primary source of energy and its actual use. Therefore, TES system is a tool which not only reduces the gap between demand and supply but also improves the performance and reliability of the system and plays an important role in energy conservation and management.

Energy storage is useful, when Energy supply is limited and Energy cost is time dependent. The cold TES also supports Load leveling, Peak-shifting and DSM.

The demand for electricity in Sri Lanka is continuously increasing, growing at an average rate of 5.4% per year [1]. Additional power plants must be constructed to satisfy this demand. It was estimated that Sri Lanka must invest around US$ 5 billion over the next ten years [1] to finance an expansion program for an additional 1,800 megawatt (MW) of electricity to cope with this predicted demand. Therefore, shifting air conditioning load to off peak hours using storage methods will reduce the investment on costly generation plants.

1.2. Power Sector in Sri Lanka

Sri Lankan power system can be divided into three main categories namely Generation, Transmission and Distribution based on their operations. Generation sector consist of CEB hydro, CEB Coal, CEB thermal, IPP thermal and SPP power plants.

Ceylon Electricity Board (CEB) is the only transmission licensee and responsible for controlling the power system in Sri Lanka. CEB purchases energy from generation plants in an optimum way to meet the demand in real time. Generation mix of 9th March 2016 is shown in Figure 1. Energy consumption of a day is around 40 GWh.

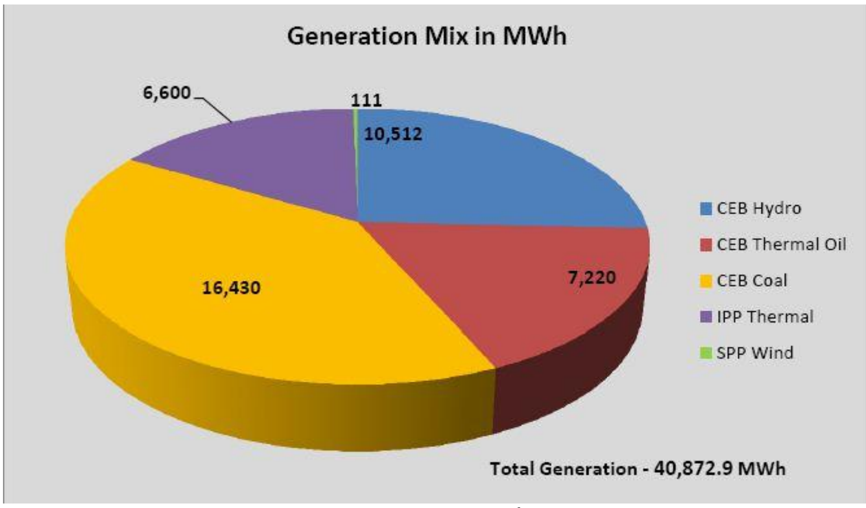

Figure 1: Generation Mix of 9th March 2016
Source: Generation and Reservoirs Statistics, 9th March 2016, PUCSL

CEB is responsible for operating the power system in least cost method to reduce generation cost of the system. CEB decides the capacity and time frame for each and every power plant to dispatch based on the least cost method. For that CEB has to consider technical constrains as well as generation cost of each and every power plant. Some power plants have startup and shutdown costs based on their technical parameters which are also considered by CEB.

Daily load profile of the power system in Sri Lanka has a high peak demand during 1830 hour to 2230 hour and low demand during 2230 hour to 0530 hour. Also there are few peaks and valleys in the day time. Figure 2 shows the load profile of the power system in Sri Lanka. The valleys and peaks in the load profile force CEB to operate high cost thermal power plants for a relatively shorter period of time which increases the total generation cost.

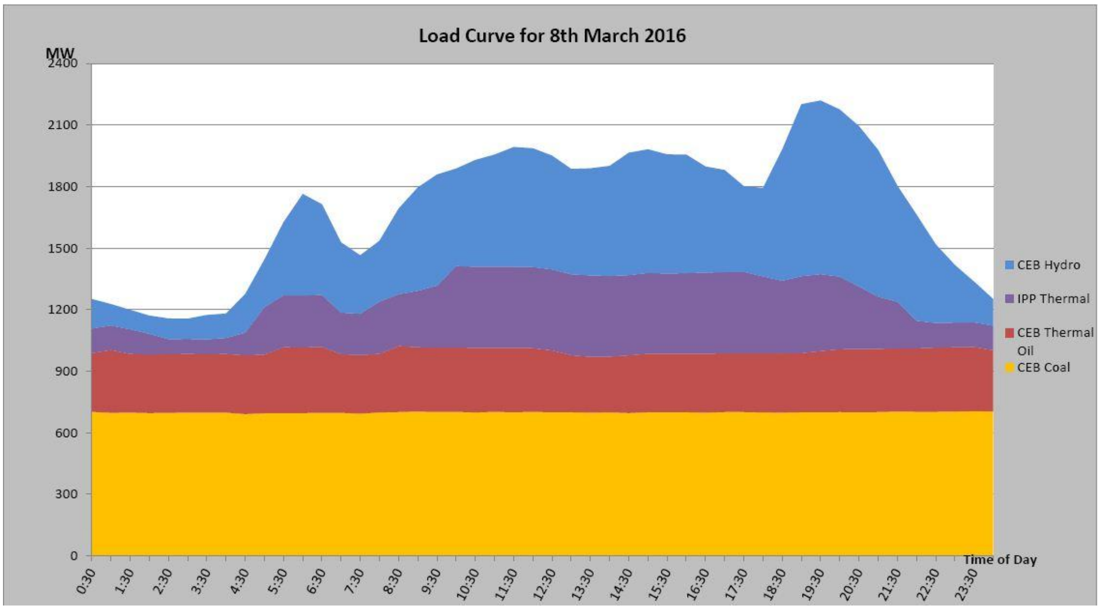

Figure 2 : Load Profile of Sri Lanka Power System, 8th March 2016
Source: Generation and Reservoirs Statistics, 9th March 2016, PUCSL

Depending on the demand pattern of load profile it can be divided in to three Time of Use (TOU) periods namely peak, off-peak and day. Time slots for peak, off-peak and day periods are shown in table 1.

Table 1: Merit Order

TOU	Off-Peak	Day	Peak
Time	2230 - 0530	0530- 1830	1830- 2230

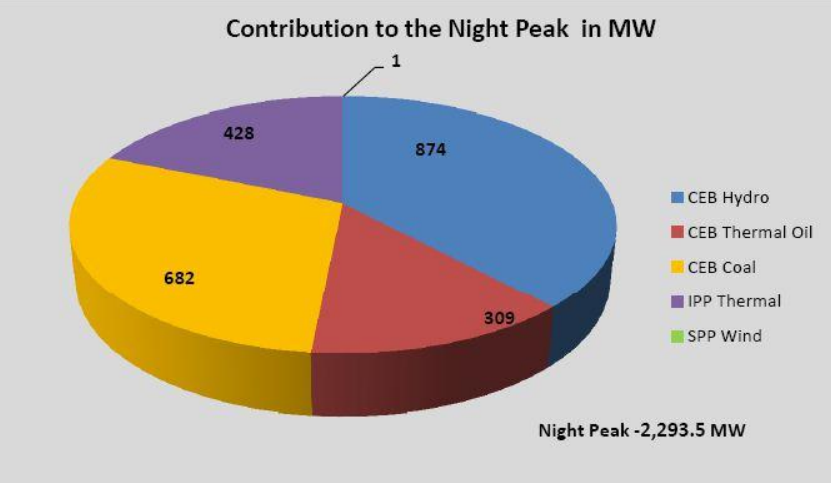

Figure 3: Contribution to the Night Peak, 8th March 2016
Source: Generation and Reservoirs Statistics, 9th March 2016, PUCSL

The night peak (evening peak) during 1830 hour to 2230 hour of 8th March 2016 is 2,239.5 MW. The contribution to night peak from different power plants is shown in Figure 3. Minimum recorded demand on 8th March 2016 is 1,142.7 MW. Due to this high evening peak CEB has to operate its high cost thermal power plants which will increase the generation cost of the system.

CEB introduced Time of Use (TOU) tariff structure to mitigate this issue by motivating the commercial, industrial, and hotel customers to shift their load from peak to off-peak period. Present TOU tariff published by the PUCSL is given in Table 2.

Table 2: Sri Lankan Tariff Structure, effective from 15th Nov 2014

Tariff Category	**Units**	**Unit Charge (LKR/kWh)**			**Fixed Charge (LKR/Month)**	**Demand Charge (LKR/kVA)**
		Peak	Off-Peak	Day		
		(1830hr - 2230hr)	(2230hr-0530hr)	(0530hr-1830hr)		
General Purpose						
GP-1 <42 kVA	< 211 units		18.30		240	-
	> 210 units		22.85		240	
GP-2	-	26.60	15.40	21.80	3,000.00	1,100.00
GP-3	-	25.50	14.35	20.70	3,000.00	1,000.00
Industrial Purpose						
I-1 <42 kVA	< 301 units		10.80		600	-
	> 300 units		12.20			
I-2	-	20.50	6.85	11.00	3,000.00	1,100.00
I-3	-	23.50	5.90	10.25	3,000.00	1,000.00
Hotel Purpose						
H-1 <42 kVA	-	21.50			600	-
H-2	-	23.50	9.80	14.65	3,000.00	1,100.00
H-3	-	22.50	8.80	13.70	3,000.00	1,100.00

1.3. Hotel Industry

Hotel industry in Sri Lanka is developing rapidly with the development of tourism industry since the eradication of three decade long separatist terrorist insurgency in May 2009. According to Central Bank of Sri Lanka (CBSL), the hotel industry contributed around two percent to the country's Gross Domestic Product (GDP) in 2011 [7]. With the development of hotel industry, demand for energy is rapidly increasing. Therefore, there is an essential requirement for DSM in hotel industry.

In a large hotel HVAC system consumes around 60% of its total electricity consumption [14]. If further analyzed, 30% to 40% of electricity consumption of the HVAC system is from the central plant which consists of chillers and cooling towers. Break down of electrical energy use in a typical hotel building is given in Figure 4 [14].

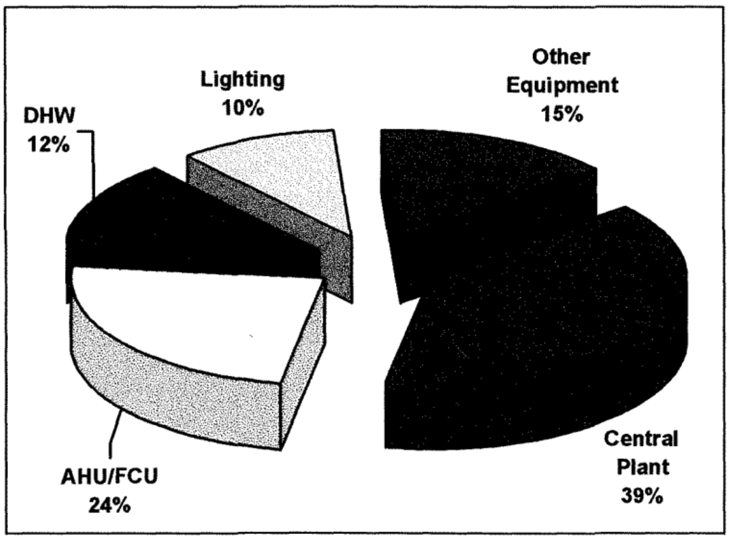

Figure 4: Breakdown of Energy Consumption of a Large Hotel
Source: [14]

Therefore, using energy conservation methods with the central plant is more important as it is the single largest electricity consumer of a hotel.

1.4. HVAC System

Heating, ventilation, and air conditioning (HVAC) is the technology of indoor environmental comfort. Its goal is to provide thermal comfort and acceptable indoor air quality. HVAC system design is a sub-discipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and heat transfer.

HVAC is an important part of residential structures such as apartment buildings, hotels and medium to large industrial and office premises where safe and healthy building conditions are regulated with respect to temperature and humidity, using fresh air from outdoors.

An HVAC system consists of Chiller, Cooling Towers, Pumps, Air handling units, Fan coil units, Duct work, Refrigerant lines and Vents. Figure 5 shows the basic cycles of HVAC system.

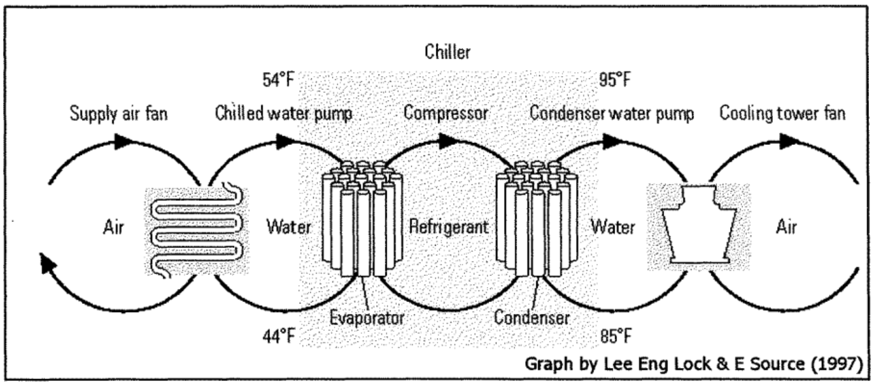

Figure 5: Basic Cycles of HVAC system
Source: [14]

1.4.1. Chiller

There are several chiller types used in an HVAC system. Most commonly, they are absorption, centrifugal, rotary, and scroll. Depending on the cooling method of the chillers they can be either air-cooled or water-cooled. Compression chiller components include an evaporator, compressor, condenser, and expansion device. Figure 5 shows the major components of a chiller.

In HVAC systems, a pumping system circulates cool water or a water/Glycol solution from the chiller to cooling load. This chilled water removes heat from the area to be cooled and the warm water returns to the chiller. Chillers contain a chemical compound, called a refrigerant. There are many types of refrigerants and applications depending on the temperatures required but they all work on the basic principle of compression and phase-change of the refrigerant from a liquid to a gas and back to a liquid. This process of heating and cooling the refrigerant and changing it from a gas to a liquid and back again is the refrigeration cycle.

The refrigeration cycle starts with a low-pressure liquid/gas mixture entering the evaporator. In the evaporator, heat from the returned chilled water or water/Glycol solution is absorbed by the refrigerant, which changes it from a low-pressure liquid to a low-pressure gas. The low-pressure gas enters the compressor where it is compressed to high-pressure gas. The high-pressure gas enters the condenser where ambient air or condenser water removes heat from the refrigerant which change the refrigerant to high-pressure liquid. The high-pressure liquid travels through the expansion valve, which controls how much liquid refrigerant enters the evaporator, thereby beginning the refrigeration cycle again.

1.4.2. Cooling towers

Cooling towers are used as heat rejection devices in HVAC system. They are installed outside of the building and condensed water is circulated through the cooling tower to get cooled. Refrigerant in the refrigeration cycle is condensed by transferring heat to the water through heat exchanger. Heat absorbed from the refrigerant increases the temperature of the condenser water and must be cooled to permit the cycle to continue. The condenser water is then circulated through the cooling tower where evaporative cooling causes heat to be removed from the water and added to the outside air. The cooled condenser water is then piped back to the condenser of the chiller. A cooling tower is a latent heat exchanger, where the magnitude of heat flow is a function of the quantity of water that is evaporated which is primarily a function of the relative humidity of the outside air.

1.5. Identification of the Problem

With the current time of day tariff structure there is a financial saving to the customers who can shift their loads from peak and day to off peak hours. But generally only industrial category customers are taking the benefit of the TOU tariff structure by scheduling their work shifts by reducing the power consumption in the peak hours.

General purpose and hotel industry consumers are not interested in taking this benefit of TOU tariff structure as their services cannot be reduced or shifted to another time slot. But if we consider the HVAC systems with chillers there is a possibility of shifting air conditioning load to off peak hours to take the maximum benefit from the TOU tariff structure.

Among general purpose consumers, most of their HVAC and other loads are in the day hours. Only few loads are available in the peak hours. But as far as the hotel sector is concerned, their loads span throughout the day. With the present TOU tariff structure there is more benefit to the customers who shift their loads from peak hours to off peak hours rather than customers shifting loads from day hours to off peak hours. Therefore hotel customers will benefit more than General Purpose customers by shifting HVAC loads to off peak hours.

1.6. Research Objectives

The objective of this research is to identify the economic benefits of shifting Air Conditioning loads from Peak and Day to off peak hours through a case study for a large scale hotel.

Following actions were carried out in this study.

- Identification of the Air Conditioning system of the hotel.
- Identification of the Air Conditioning load pattern and energy consumption of the equipment of the HVAC system.
- Identification of the optimum cooling load to be stored.

- Identification of the best and cost effective technology to be used for the storage.
- Identification of the optimum operation hours of the chiller plant,
- Evaluation the economic benefit to the industry and to the CEB.

Cinnamon Lakeside Hotel was selected for this case study.

1.7. Cinnamon Lakeside Hotel

Cinnamon Lakeside Hotel enjoys a prime location in the heart of Colombo and it is one of the largest five star hotels in Sri Lanka.

It consists of 380 rooms and two function halls. There are 358 rooms including 22 suites, Business Centre, Executive Lounge, Fitness Centre & Health Club, Outdoor Swimming Pool, Tennis & Squash Courts, and Spa.

1.8. Organization of the Thesis

After this introductory chapter, Chapter 2 gives an analysis of the existing HVAC system of the Cinnamon Lakeside Hotel. This analysis is conducted to identify and find out the possibility of using storage methods to shift air conditioning load. Chapter 3 covers the TES technologies available which are analyzed to identify the best TES technology for the study. In Chapter 4 a technical evaluation is conducted on Ice Storage and Chilled Water Storage (CWS) under six scenarios in order to identify the potential savings that can be obtained from storage methods. Chapter 5 presents the financial viability and the feasibility of the results obtained in Chapter 4. The final chapter provides conclusions and recommendations based on the results obtain in Chapter 4 and Chapter 5.

2. HVAC SYSTEM OF CINNAMON LAKESIDE HOTEL

2.1. Chiller Plant

Cinnamon Lakeside Hotel has a Single Screw DAIKIN Chiller with a capacity of 455 TR. Its parameters are given below.

- User Mode Cap = 1,598.4 kW_R
- Coefficient of Performance (COP) = 5.65
- Power Input = 283 kW
- Voltage = 400 V (3ph)
- Frequency = 50 Hz

Figure 6: Name Plate Data of Chiller in Cinnamon Lakeside Hotel

The Coefficient of Performance (COP) of an air conditioning system is the ratio of useful heating or cooling provided to work required. Higher COP equate to lower operating costs. The COP usually exceeds 1 in chiller plants.

$$\text{COP} = \frac{\textbf{User Mode Capacity}}{\textbf{Power Input}} \qquad (1.1)$$

A ton of refrigeration (TR), is a unit of power used to describe the heat extraction capacity of refrigeration and air conditioning equipment. It is defined as the rate of heat transfer that results in the melting of 1 short ton (2,000 lb.; 907 kg) of pure ice at 0 °C in 24 hours.

A ton of refrigeration (TR) is approximately equivalent to 12,000 BTU/h or 3.51 kW_e.

2.2. Cooling Towers

HVAC system of Cinnamon Lakeside Hotel consists of two 300 TR cooling towers. These towers are operating at full load throughout the day.

2.3. Load Profile

24 days load profile of the chiller plant was taken from its Building Management System (BMS). Table 3 shows the days which load profile was taken.

Table 3: Days which Chiller Load Profile Taken

2016 - May -05	2016 - Aug - 09	2016 - Nov -14
2016 - May -06	2016 - Aug - 10	2016 - Nov -15
2016 - May -07	2016 - Aug - 11	2016 - Nov -16
2016 - May -08	2016 - Aug - 12	2016 - Nov -17
2016 - May -09	2016 - Aug - 13	2016 - Nov -18
2016 - May -10	2016 - Aug - 14	2016 - Nov -19
2016 - May -11	2016 - Aug - 15	2016 - Nov -20
2016 - May -12	2016 - Aug - 16	2016 - Nov -21

Average load profile of 24 days is taken for the analysis of the chiller plant. Figure 7 shows the average load profile of the chiller of Cinnamon Lakeside Hotel.

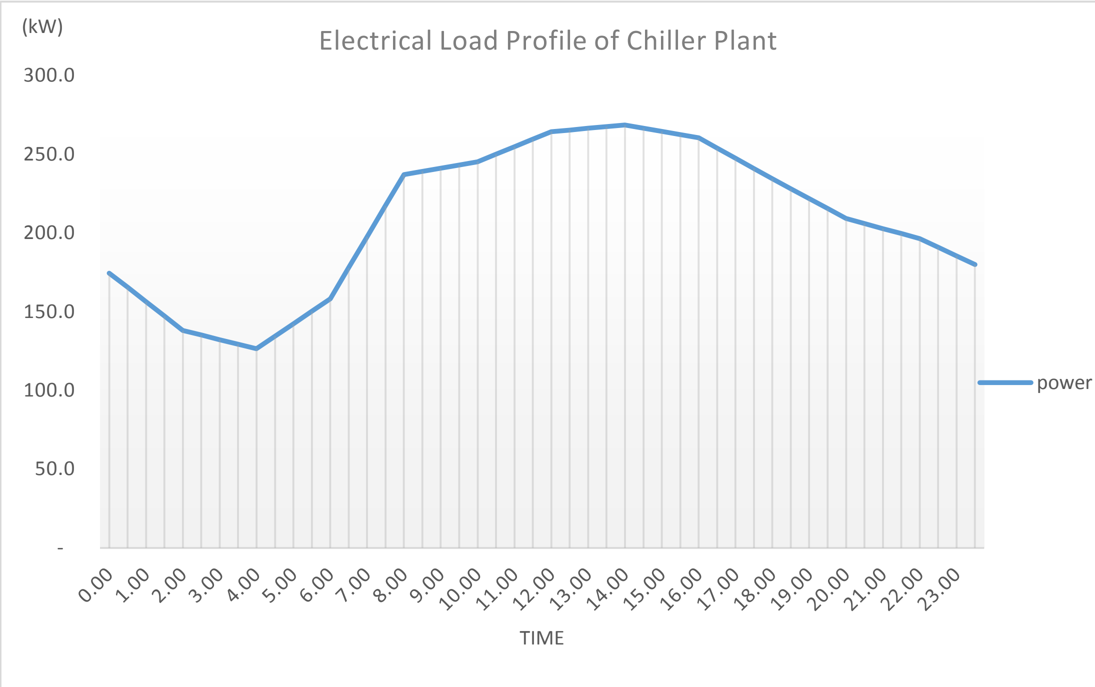

Figure 7: Average Electrical Load Profile of Chiller

The average load profile of the chiller shows that there is a low Air Conditioning (AC) load during of-peak hours compared to that of the other times of the day.

Table 4 shows the breakdown of cooling load in Time of Use (TOU) time slots calculated using the average load profile of the chiller plant shown in Figure 7.

Table 4: Breakdown of Load Profile

	off Peak (22.30 – 05.30)	**Day (05.30 – 18.30)**	**Peak (18.30 – 22.30)**	**Total**
Energy (kWh_e)	1048.9	3156.9	821.3	5027.1
Cooling Load (kWh_R)	5926.2	17836.7	4640.1	28403.0
Cooling Load (TRh)	1688.4	5081.7	1322.0	8092.0

3. METHODS OF SHIFTING AIR CONDITIONING LOAD

The load profile of chiller plant analyzed in Chapter 2 shows the possibility of shifting AC load from peak and day to off-peak hours as there is a low demand in off-peak compared to the day and peak hours. Shifting of AC load can be done using TES methods. Depending on the storage medium used, TES can be divided into two categories; chilled water storage and ice storage. In this chapter it is expected to identify the best TES technology to be adopted for Cinnamon Lakeside Hotel by analyzing both technologies in detail.

3.1. Thermal Energy Storage (TES)

The concept of using TES is to store energy in non-peak hours where demand for the energy is low to use in peak hours. TES in air conditioning system is a cold water storage where conventional energy is used to cool the storage water. Energy is basically transferred to achieve the temperature difference in storage water that can be used during peak hours where energy rates are comparatively high [3].

Storage medium for TES systems should be able to store energy for later use and it should have a high thermal capacity. Energy can either be stored as sensible (chilled water) or as latent heat (ice). The storage medium selected should have high thermal capacity in order to reduce the storage volume. Water meets this requirement since it has the highest specific heat (4.19 kJ/kg.K) of all common material and it is inexpensive [6].

Latent heat thermal energy storage is particularly attractive due to its ability to provide high energy storage density and its characteristics to store cold at constant temperature corresponding to the phase transition temperature of phase change material. In addition to that, ice storage is a proven technology that reduces chiller and other equipment sizes used in HVAC system.

Advantages of TES

Energy cost saving: When electricity price in peak hours is higher than off-peak hours, cold thermal storage provides the potential for using off-peak energy to produce cooling which can be used in peak hours. This helps in reducing the cost on electricity. Additionally, a cool storage system can increase the efficiency and plant load factor of a chiller plant and thus increase the cost effectiveness.

Reduced chiller size: TES allows to design chillers to meet the average load instead of peak cooling load. This will reduce the size of chillers and auxiliary equipment (pumps and fans).

Capital cost saving: reduction in the size of equipment reduces the capital investment for new HVAC systems and savings will be more than the investment cost on storage system. Reduction in equipment size such as chillers, fans and pump motors reduce the electricity demand of the HVAC system which reduces the size of the transformers and electrical distribution system [2].

Operation cost saving: when TES are used chillers will always operate near 100% capacity during charging the storage. Also the capacity factor of the chiller is high compared to the conventional chilled water system. This reduces the amount of time chiller will operate at low load condition as well as on/off cycles. When chillers are operating at full capacity continuously they require less maintenance.

Energy saving: The main purpose of TES is shifting of energy instead of conserving energy. But indirectly it may be able to reduce electricity consumption of the HVAC system. Operating chillers more at night during which lower condensing temperatures improve equipment efficiency and allowing chillers to operate at full load will increase efficiency [2]. Low temperature fluid distribution will reduce the energy consumption of pumps by approximately 40% and low temperature air distribution will reduce the energy consumption of fan coil units by approximately 50%. This reduction will provide energy savings over the life time of the system.

Back up capacity: The capacity of the existing system can be increased by installing a TES system rather than adding conventional non storage equipment. Any backup cooling required can be taken from the storage.

Increased flexibility: With TES system, cooling can be available on any desired schedule independent of the operation of chillers (within limits). Chillers are not designed to load and unload quickly. TES can respond quickly and efficiently to load variations and can track rapid changes in the cooling load [6]. It is also possible to extend the capacity of existing system by using TES system instead of investing on non-storage equipment [2].

3.1.1. Chilled water storage (CWS)

CWS is a TES using sensible heat of water to store energy during off-peak hours. Vertical cylinder tanks are the most common shape of tanks used for CWS [2] and tank can be located above ground, partially buried or completely buried depending on the location. Tank capacity depends on the amount of cooling load to be stored and temperature difference between stored chilled water and return water. Separation of cooler and warmer chilled water in the same tank is achieved using thermal stratification method due to its simplicity, reliability and low cost [2].

Stable density gradient prevents mixing of the two volumes. The thermal separation of water at two temperature levels is achieved by placing the warmer, less dens return water at the top of denser, chilled water of the tank. Chilled water is taken at a low velocity in horizontal flow so that buoyancy forces dominate the inertial effects. Figure 8 shows the thermocline properties in a CWS tank. One to two feet thermocline form in the tank between warmer and cooler chilled water which minimize further mixing of warmer and cooler chilled water above and below the thermocline [2]. Diffusers are used to enter and leave water without causing significant mixing inside the tank [2].

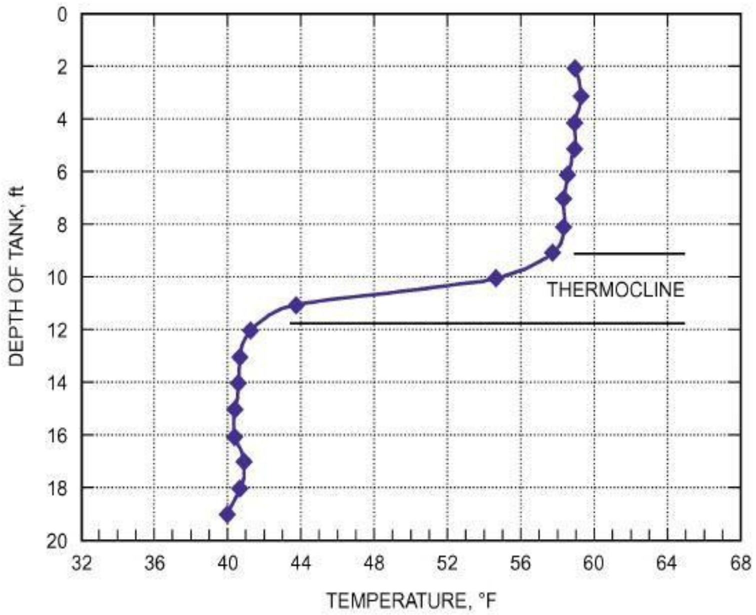

Figure 8: Stratification profile of the storage tank

Advantages of CWS system

CWS systems have several advantages over the ice storage and phase change systems.

- Existing HVAC system can be easily modified into CWS by adding only storage. Therefore investment is low compared to latent heat storage systems.
- Conventional chillers can be used. Energy consumption is low due to high Coefficient of Performance of conventional chillers compared to Glycol chillers.
- Storage medium is water which is less expensive and non-toxic.
- No secondary coolant is used, hence heat exchanger is not required.
- Efficiency of the HVAC system is higher compared to existing system because chillers will operate more at night during which condensing temperature is low. Low ambient temperature in night time improves the performance of heat rejection equipment.
- System is very similar to the existing system and using of conventional chillers reduces the complexities in operation and maintenance. No special training is needed for the operations staff.

- System designing will be familiar since the system is designed on the supply water temperature that is used in conventional chiller systems. [2]

Disadvantages of CWS system

- The volume of the storage tank is larger than latent heat storage systems for the same cooling load. Therefore finding the required space may be difficult.
- System losses are high due to the large surface area of the tank.
- Required large volume of chilled water. This will increase the cost of maintenance and water treatment.
- Technical difficulties faced to avoid mixing of chilled water with the warm returned water.
- Skilled construction is required when building the tank in order to avoid any leaks or cracks in the tank.

3.1.2. Ice storage

Ice storage is a proven technology that reduces chiller size and shifts compressor load, condenser fan and pump loads from peak periods to off-peak periods, where electrical energy is less expensive.

The latent heat of fusion of water (phase change of water to ice or ice to water) is used in this process to store cooling load. Water is used as a phase change storage medium in order to take advantage of its higher storage capacity [6].

There are mainly four types of ice storage systems.

- Static Ice Systems
- Dynamic Ice Systems
- Ice Slurry Systems
- Encapsulated Ice Systems

3.1.2.1. Static ice systems

Static ice system is also known as the ice building system. The static system is more compact and less costly than dynamic systems. In this system, ice produces around multiple coils or tubes that are submerged in a storage tank filled with water. Through the coils a fluid that has a lower freezing temperature than water is circulated. The fluid that is mostly used is water/Ethylene Glycol solution. Since the temperature of the fluid has a lower freezing point temperature than water, ice is formed at coil surface. The formed ice is then melted from inside out during the discharge cycle. [6]

The chiller operates during off-peak hours cooling a Glycol solution to sub-freezing temperatures which is then circulated through the ice storage coils. Ice forms around the external surfaces of the coils, and a full storage charge is reached when the ice is typically 1.1 to 1.5 inches thick. The ice is ultimately melted and used as a cooling agent. There are two different methods of ice melt; External Melt and Internal Melt.

External melt

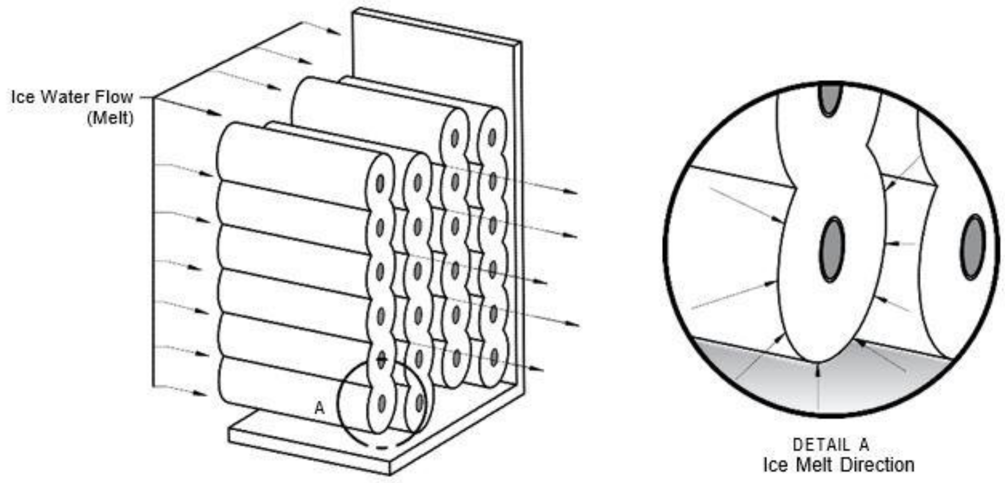

Figure 9: External Melt Method
Source: [6]

The ice build is complete when there is a ring of ice of the desired thickness around each coil circuit. At full build condition, the storage container will have approximately

65% ice and 35% water. The ice storage coils are spaced so that the warmer returning chilled water will circulate through the storage container and flow around and over these ice coil surfaces. The ice is melted from the outside of the ring, thus the term external melt. This resulting ice melt circulates to cool the chilled water system. External melt systems use two different fluids. Glycol is the ice build fluid and is circulated through the coil circuits, and water is the ice melt fluid providing the cooling to the system. Because there are two different fluids (Glycol and ice water), more control components may be required for external versus internal melt systems [6].

The advantages of an external melt system are:

- Ice water supplied to the system is at a temperature of 1.1°C or lower.
- Since there are no restrictions to the ice water flow, the rate of ice melt can vary greatly. The rate of ice melt can be constant (over 8-10 hours), rapid (melting all the ice in a short period of 1-2 hours), or fluctuating that satisfies the cooling requirements for air conditioning or process applications.
- The thermal ice storage cooling water is often the same as the cooling system fluid.
- Best overall system efficiency. Since the chiller and associated pumps are turned off during the on-peak hours, the only energy input is from the ice water pump. The on-peak system efficiency is often as low as 0.20 kW/ton.

The disadvantage of an external melt system is:

- The ice water in the storage container is exposed to atmospheric pressure. The cooling system loop must be designed as an open system with the ice water pump suction connection located below the water level of the storage container.

Internal melt

The ice build is complete when the water in the storage container reaches a predetermined level. The volume in the storage container may be 65% to 80% ice. The ice thermal storage coils are located closer together, than for external melt designs, and the formation of ice on the coils is allowed to bridge from coil to coil. During the build cycle, the sub-freezing Glycol solution is circulated through the ice coil circuits. During the ice melt cycle, the warmer returning Glycol solution is circulated through the same ice coil circuits, and ice is melted from the inside of the ring. Thus the term internal melt [6].

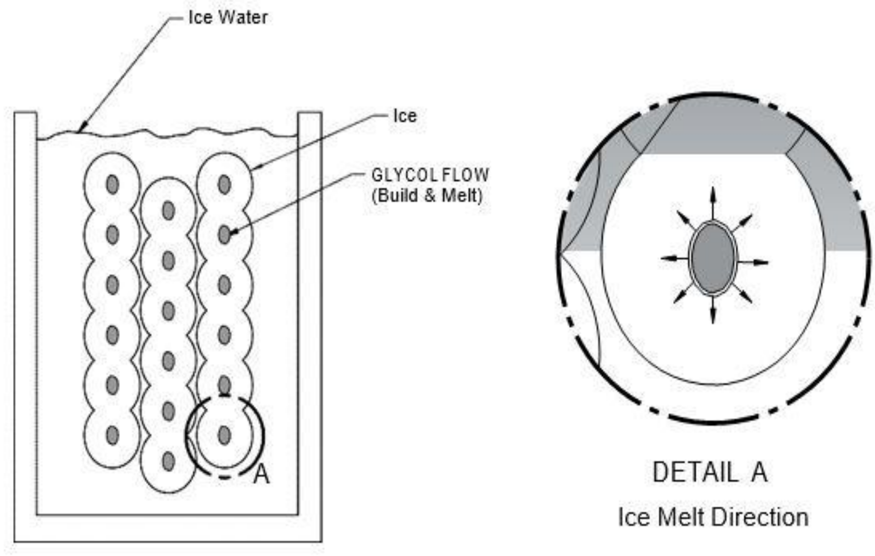

Figure 10: Internal Melt Method
Source: [6]

Advantages of an internal melt system are:

- The cooling system is a closed loop.
- Water in the storage container remains static and goes through phase changes only. This water is not circulated in the cooling system.
- Since it is a closed loop, controls are simple.
- Minimum leaving Glycol temperature is typically 3°C. Not as low a temperature as with external melt systems but still well below conventional chilled water system designs.

Disadvantages of an internal melt system are:

- The cooling liquid is the Glycol solution.
- The Glycol flow rate is limited due to the pressure drop through the ice storage coil. A limited flow rate also limits the rate of ice melt. The thermal ice storage system may not be able to track rapid cooling load fluctuations.

3.1.2.2. Dynamic ice systems (ice harvesting)

In dynamic ice storage systems, the ice is formed in the evaporator surface and once a certain ice thickness is achieved, it is removed and stored in a storage container. The removal of ice can be achieved through mechanical means or through injection of hot gas into the evaporator plates. The ice producing unit has to be placed on top of the storage container [2]. Chilled water from the storage tank is pumped from the storage tank and the returned warm water is sent to the ice generator [2].

3.1.2.3. Ice slurry system

Ice slurry systems form small ice particles within a liquid of Glycol, Sodium Chloride, or Calcium Carbonate solute in water. The solute concentration is around 2% to 10% by mass [2]. The ice particles are formed near the inside surface of cylinders of orbital rod evaporator. The solution is cooled by the evaporating refrigerant and ice particles are formed. The formed particles can either be dropped directly or pumped into the storage tank. Discharge is achieved by pumping the cool solution from tank either directly through the cooling load or through an intermediate heat exchanger that isolates the cooling load from the ice slurry system. The warm solution is returned to the top of the tank distributed over the ice slurry through multiple spray nozzles [3].

3.1.2.4. Encapsulated ice system

Encapsulated ice systems use large number of small sealed plastic containers filled with water and nucleating agent which are placed in a storage tank. Most common type is spherical containers stored in concrete or steel tank with insulation. Freezing and melting of water happens in the plastic container. Charging and discharging of the encapsulated ice system is similar to internal melt systems described in section 3.1.2.1. Size, type and shape of the storage tank is selected based on achieving even flow of heat transfer fluid between the containers.

In the charging cycle secondary coolant (Glycol solution) which is cooled to about -4°C using Glycol chiller is circulated through the storage tank. Leaving temperature of the secondary coolant during discharge varies with the flow rate, and ice inventory of the storage. During the discharge cycle warm coolant returning from heat exchanger is circulated through the tank to get cooled by the stored ice in the plastic containers. [2]

Advantages of ice storage systems

Ice storage system has several advantages,

- The storage volume required is lower than CWS, therefore a larger cooling capacity can be achieved by a given storage volume.
- The space requirement for the storage tank is low due to the use of ice as heat storage medium.
- Storage thermal losses are less due to the lower surface area of the storage tank.
- Water treatment and maintenance cost is lower due to the amount of water required is lower for the circulation.
- Tanks can be factory built. [6]

Disadvantages of ice storage systems

- Since the chiller suction temperature is low, there is a limited selection for machinery.
- The efficiency of the refrigeration cycle will reduce due to the lower suction temperature.
- Increased expenses on training the operational and maintenance personnel, since unconventional equipment are used.
- Some control problems exist in the static systems in measuring the ice level [6].

3.2. Operating Strategy

Operating strategy is the next step of designing a TES for the existing HVAC system of Cinnamon Lakeside Hotel. For deciding the operation strategy it is important to decide the type of storage required to store the cooling load; A full or partial storage.

The term Full Storage refers to systems where the entire system load is cooled from the storage. The term Partial Storage refers to systems where only a portion of the system cooling comes from the storage.

Full storage systems provide the largest amount of energy cost savings. Mechanical cooling components compressors, condenser pumps and fans do not operate during peak and day hours. However, the system may also have the highest initial cost. The amount of storage equipment required may be considerably more than required for a partial storage system. Also, in order to build sufficient ice or chilled water for the full storage requirements, the capacity of the chiller may be larger than that required for a comparable conventional chilled water system. Both of these cost additions may offset the energy cost savings [6].

In this study full storage for shifting both peak and day cooling load and shifting of only peak is analyzed to identify the benefit to industry as well as to the utility.

3.3. Summary

The objective of this study is to identify the most suitable storage technology for the Cinnamon Lakeside Hotel. The proposed storage system should be able to convert the existing HVAC system to storage system with the optimum investment on the existing system. From the above analysis it was identified that CWS and static ice storage (Internal Melt) technologies are the most suitable technologies for the Cinnamon Lakeside Hotel.

4. TECHNICAL EVALUATION

The main objective of this thesis is to identify the potential saving that can be achieved from shifting AC load from peak and day hours to off-peak hours using suitable storage method. Main focus of this section is to identify the possible methods of shifting AC load and the required modifications to the existing system.

4.1. Existing System

Existing HVAC system of Cinnamon Lakeside Hotel consists of one 455 TR Single Screw DAIKIN Chiller and two 300 TR cooling towers and several numbers of pumps, fan coil units.

Average load curve pattern of the chiller plant is shown in the Figure 11.

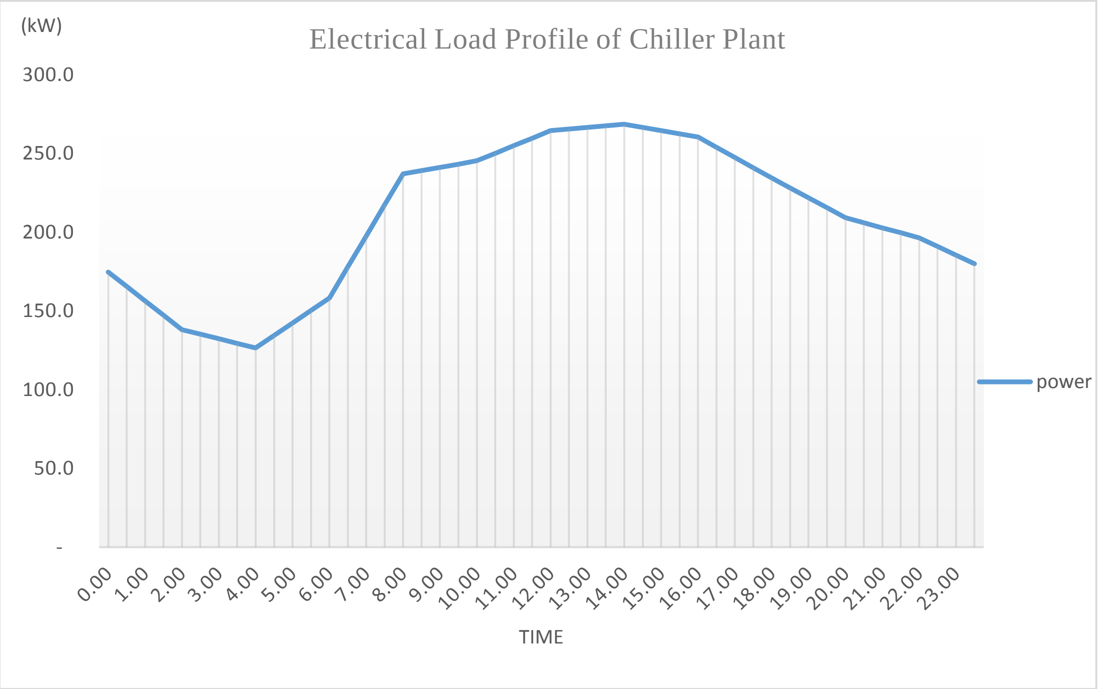

Figure 11 : Average Electrical Load Profile of Chiller Plant

Daily load curve pattern shows that there is a possibility of shifting cooling load to off peak hours as there is a low demand in the off peak hours compared to the peak and day hours.

Break down of the energy consumption of chiller in TOU time slots is shown in the Table 5.

Table 5 : Energy Consumption of Chiller

TOU	Energy (kWh)
off peak	1,048.9
Day	3,156.9
Peak	821.3
Total	**5,027.1**

Two 300 TR cooling towers are operating at its full load throughout the day and each cooling tower is rated 7.5 kW at full load. The energy consumption of the cooling towers in the TOU time slots is shown in the Table 6.

Table 6: Energy Consumption of Cooling Tower

TOU	Energy (kWh)
Off Peak	105.0
Day	195.0
Peak	60.0
Total	**300.0**

4.2. Methods of Air Conditioning Load Shifting

Ice Storage System and Chilled Water Storage Systems are selected as possible load shifting methods and further analyzed in this section. AC load shifting can be categorized into six cases depending on shifting of both peak and day or only peak cooling load. Figure 12 shows the six cases of AC load shifting studied in this section.

Following parameters are taken in to account when calculating the energy consumption of each methods.

- Heat exchanger energy loss 01% [6]
- Ice Storage energy loss 01% [6]
- Chilled Water Storage energy loss 10% [2]

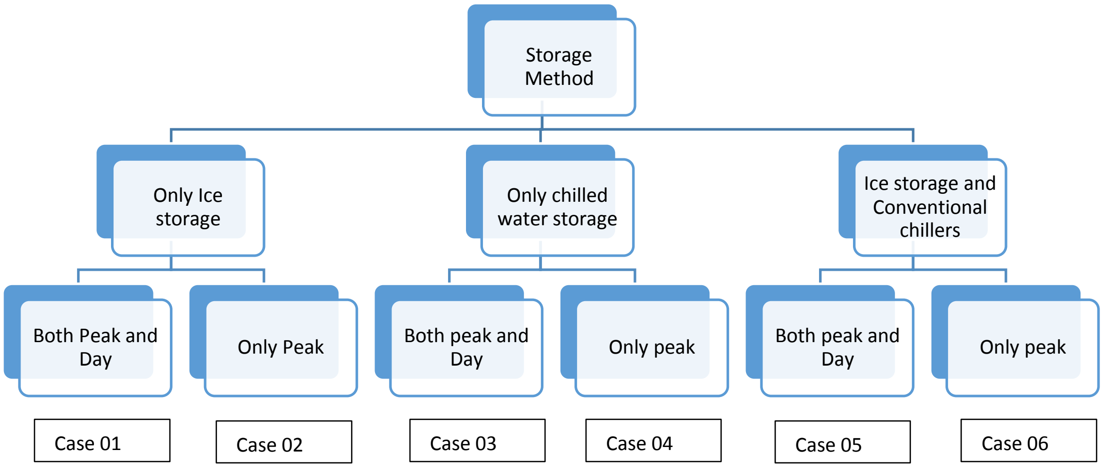

Figure 12: Methods of Load Shifting

4.2.1. Using only Glycol chillers and ice storage systems

Using only ice storage is the first major method of shifting AC load which is discussed in this section. Glycol chiller is necessary for ice building during off-peak hours and to meet the cooling load throughout the day as well.

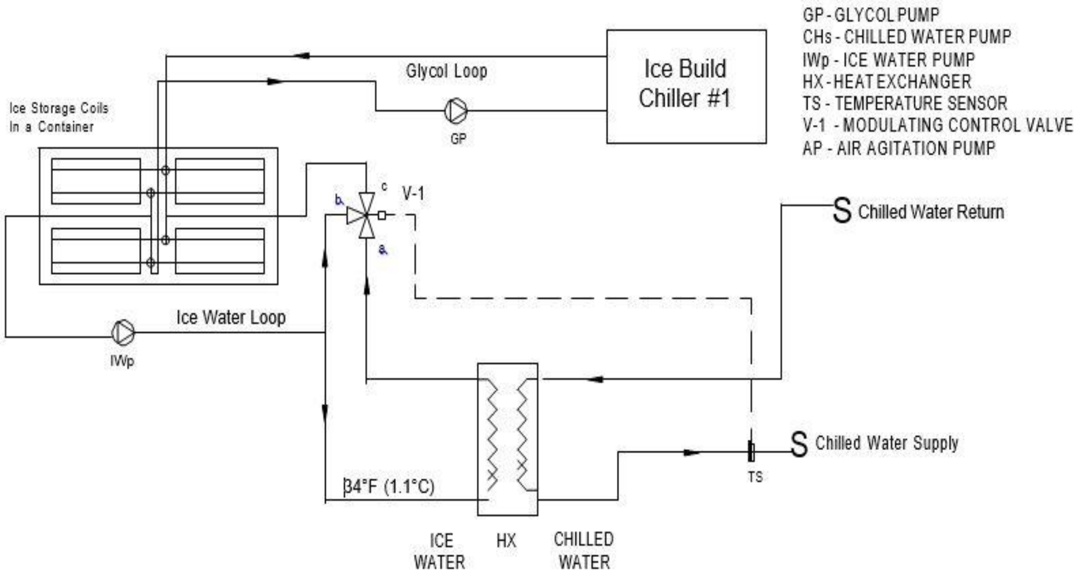

Figure 13: Ice Storage System with Glycol Chillers Only [6]

Two options were considered under this method based on the storage capacity considered for the analysis. Figure 13 shows the HVAC system with only Glycol chillers and ice storage.

Case 01: Both Peak and Day cooling load is shifted to off peak hours

Case 02: Only peak cooling load is shifted to off peak hours.

Conventional chillers are not required in both cases. Heat exchanger is used to separate Glycol loop and chilled water loop as shown in the Figure 13.

4.2.1.1. Case 01: Shifting both peak and day cooling loads

In this case shifting of both peak and day cooling loads to off-peak hours using Ice Storage System is analyzed. Only Glycol chillers are used and total peak and day cooling load of 6,403.7 TRh should be stored during off-peak hours.

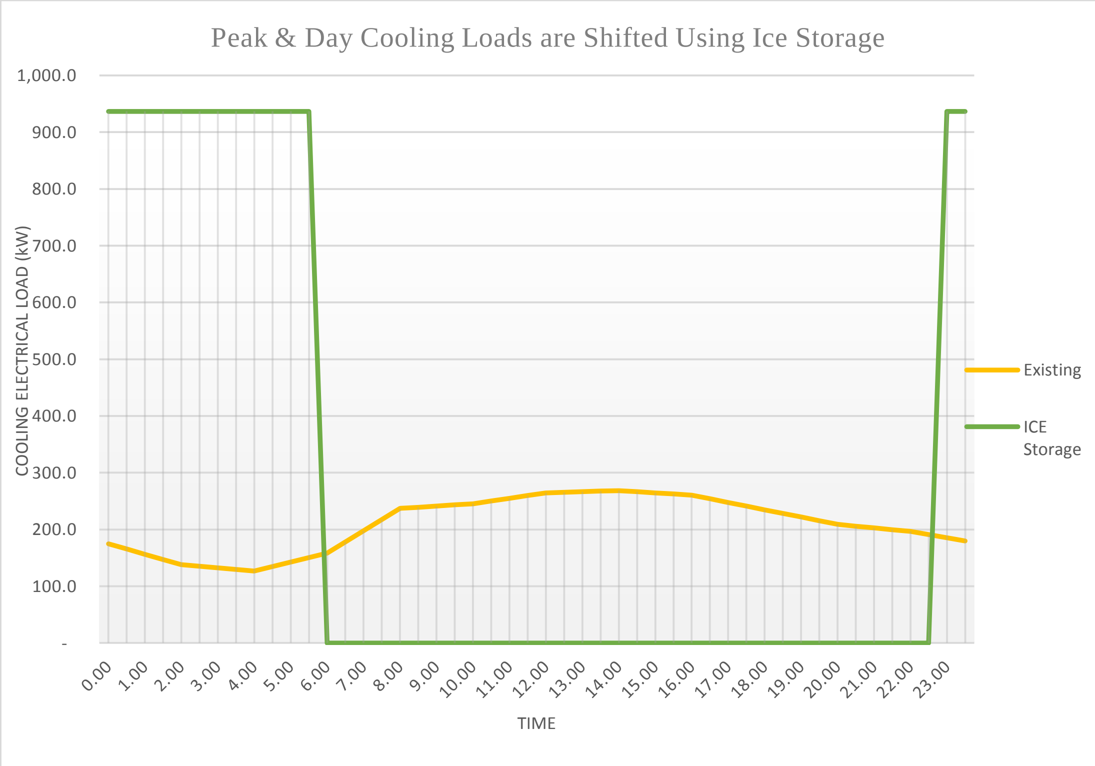

Figure 14: Load Profile of Chiller Shifting Peak and Day using Ice Storage

Glycol chiller of 1,176.80 TR (936.6 kW_e) is required for the proposed case 01. Total electrical energy consumption of the chiller is 6,556.5 kWh_e which is 1,529.4 kWh_e

higher than the existing HVAC system of the hotel. This is mainly due to supplying the off-peak cooling load from Glycol chillers and their low COP compared to the conventional chillers. Figure 14 shows the load profile of existing and proposed case with ice storage.

Case 01 required five numbers of 300 TR cooling towers. Existing system has two 300 TR cooling towers, hence three 300 TR cooling towers were added to the existing HVAC system. Cooling towers are operated only in off-peak hours and total energy consumption of the cooling towers are 262.5 kWh_e which is 97.5 kWh_e less than the existing system.

Total energy consumption is 6,819.0 kWh_e.

4.2.1.2. Case 02: Shifting only peak cooling load

In this case shifting only peak cooling load to off-peak hours using Ice Storage System is analyzed. Only Glycol chillers are used and only peak cooling load of 1,322.0 TRh should be stored during off-peak hours.

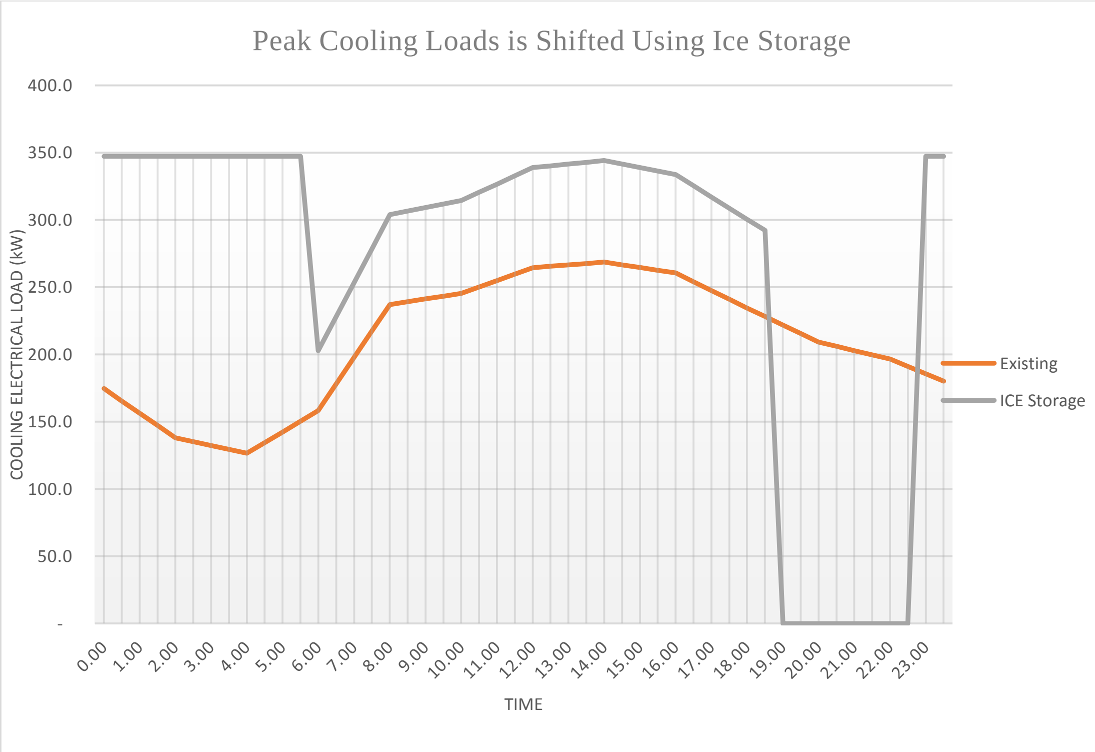

Figure 15: Load Profile of Chiller Shifting Only Peak using Ice Storage

Glycol chiller of 436.26 TR (347.2 kW_e) is required for the proposed case. Total electrical energy consumption of the chiller is 6,515.6 kWh_e which is 1,488.5 kWh_e higher than the existing HVAC system of the hotel. This is mainly due to supplying the off-peak cooling load from Glycol chillers and their low COP compared to the conventional chillers. Figure 15 shows the load profile of existing and proposed case with ice storage.

Using Glycol chillers to meet the day hour cooling load will increase the energy consumption of the chiller as the COP of Glycol chiller is lower comparing to the conventional chillers.

Case 02 required two numbers of 300 TR cooling towers. Existing system has two 300 TR cooling towers. Hence, additional cooling towers were not required. Cooling towers are operated in day and off-peak hours only. Total energy consumption of the cooling towers are 300.0 kWh_e which is 60 kWh_e less than the existing system.

Total energy consumption is 6,815.6 kWh_e.

4.2.1.3. Modifications to the existing system

- Heat exchanger is added to the system to separate Glycol and Chilled water loop.
- Ice storage is required based on the storage capacity.
- Cooling Towers will be added to the System based on the chiller capacities.
    - For Case 01 three additional 300 TR chillers were required.
    - For Case 02 no additional chillers were required.
- Two pumps were required for new chillers added to the system based on the required chiller capacities for each cases.

4.2.1.4. Advantages

- Required storage capacity is less compared to the chilled water storage.

4.2.1.5. Disadvantages

- COP of Glycol chillers are much lower compared with the conventional chillers. Therefore energy consumption of Glycol chillers are higher for the same cooling load.
- Need heat exchanger to separate Glycol loop and chilled water loop which will increase the investment.

4.2.2. Using chilled water storage systems

Using chilled water storage is the second major method of shifting AC load which is discussed in this section. Only conventional chiller is necessary to store chilled water and meet the cooling load during non-shifted period of the day.

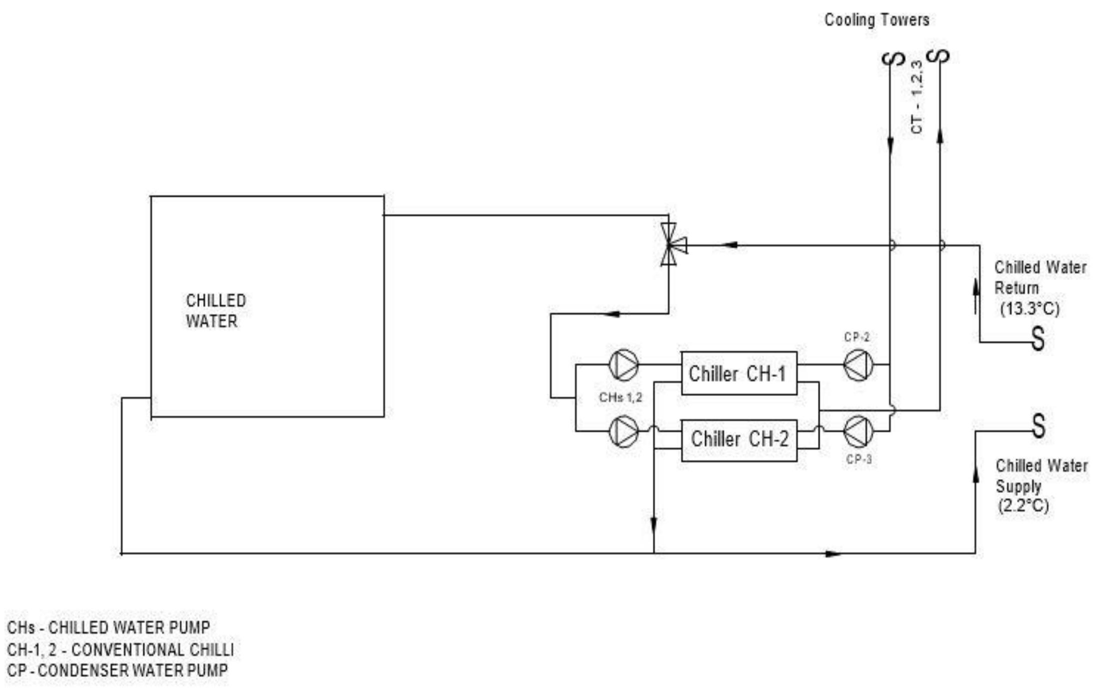

Figure 16: Chilled Water Storage System

Two options were considered under this method based on the storage capacity considered for the analysis.

Case 03: Both Peak and Day cooling loads are shifted to off peak hours

Case 04: Only peak cooling load is shifted to off peak hours.

In both cases only conventional chillers are used and existing HVAC system can be modified by adding chilled water storage as shown in Figure 16.

4.2.2.1. Case 03: Shifting both peak and day cooling loads

In this case shifting of both peak and day cooling loads to off-peak hours using chilled water storage system is analyzed. Only conventional chillers are used and total peak and day cooling load of 6,403.7 TRh should be stored during off-peak hours.

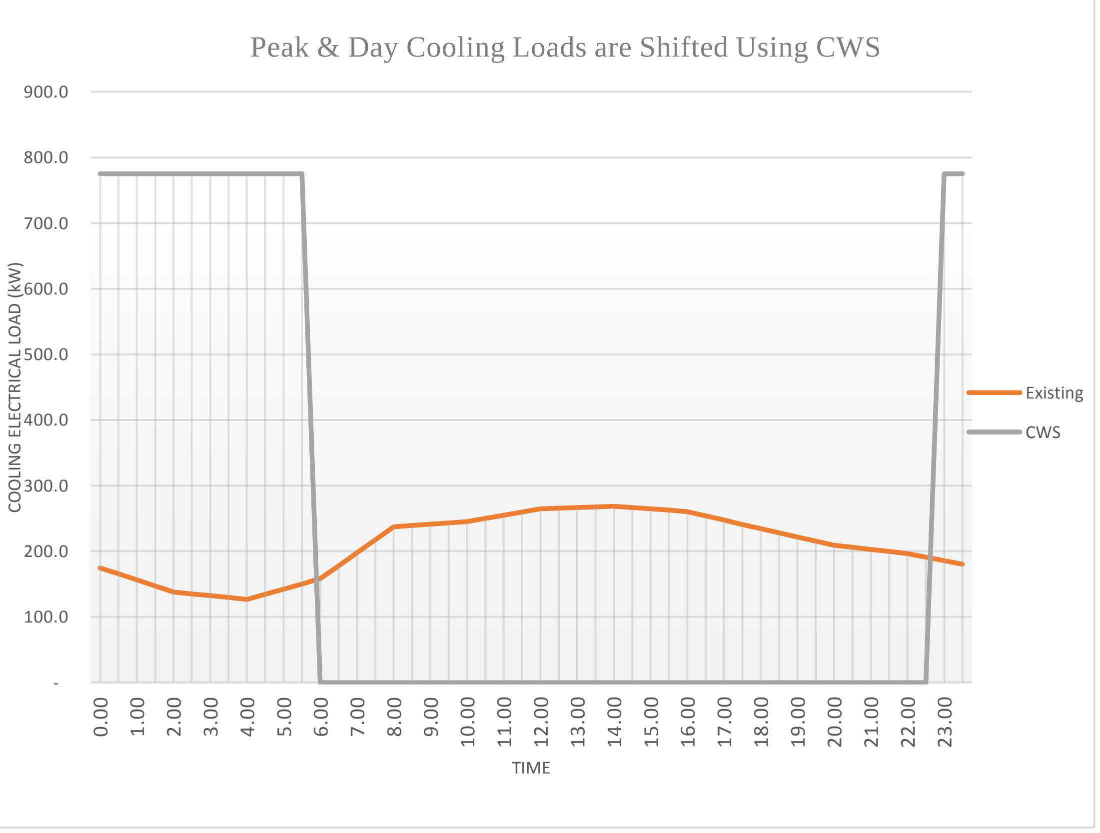

Figure 17: Load Profile of Chiller Shifting Peak and Day using Chilled Water Storage

Conventional chiller of 1,247.49 TR (774.99 kW_e) which is higher than the existing chiller capacity is required. Total electrical energy consumption of the chiller is 5,424.9 kWh_e which is 397.82 kWh_e higher than the existing HVAC system of the hotel. This is mainly due to the losses in the chilled water storage system. Figure 17 shows the load profile of existing and proposed case with CWS.

Case 03 required five numbers of 300 TR cooling towers. Existing system has two 300 TR cooling towers, hence three 300 TR cooling towers were added to the existing HVAC system. Cooling towers are operated only in off-peak hours and total energy consumption of the cooling towers are 262.5 kWh_e which is 97.5 kWh_e less than the existing system.

Total energy consumption is 5,687.4 kWh_e.

4.2.2.2. Case 04: Shifting only peak cooling load

In this case shifting of only peak cooling load to off-peak hours using chilled water storage system is analyzed. Only conventional chillers are used and total peak cooling load of 1,322.0 TRh should be stored during off-peak hours.

Conventional chiller of 448.94 TR (278.9 kW_e) which is lower than the existing chiller capacity is required. Hence, no additional chiller is needed. Total electrical energy consumption of the chiller is 5,109.2 kWh_e which is 82.1 kWh_e higher than the existing HVAC system of the hotel. This is mainly due to the losses in the chilled water storage system. Figure 18 shows the load profile of existing and proposed case with CWS.

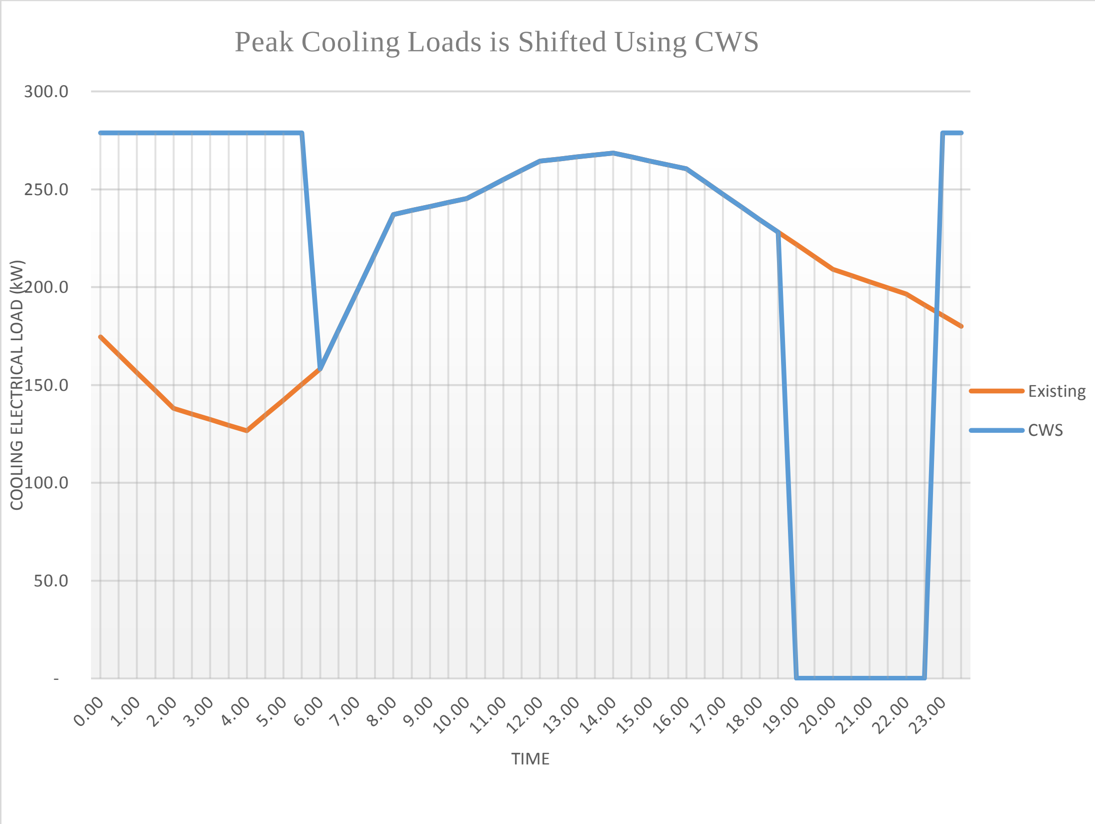

Figure 18: Load Profile of Chiller Shifting Only Peak using Chilled Water Storage

Case 04 required two numbers of 300 TR cooling towers. Existing system has two 300 TR cooling towers. Hence, additional cooling towers were not required. Cooling towers are operated in day and off-peak hours only. Total energy consumption of the cooling towers are 300.0 kWh_e which is 60 kWh_e less than the existing system.

Total energy consumption is 5,409.2 kWh_e.

4.2.2.3. Modifications to the existing system

- Chilled water storage tank is required based on the storage capacity.
- Cooling Towers will be added to the System based on the chiller capacities.
    - For Case 03 three additional 300 TR chillers were required.
    - For Case 04 no additional chillers were required.
- Two pumps were required for addition of new chillers to the system based on the required chiller capacities for each case.

4.2.2.4. Advantages

- Conventional chillers have a higher COP compared to the Glycol chillers hence energy consumption is lower compared to Case 01 and Case 02.
- Investment will be lower compared to the other methods as few modifications were required to the existing HVAC system.
- Can use existing chiller.

4.2.2.5. Disadvantages

- Chilled water storage requires large space compared to the ice storage with same cooling capacity.
- Energy losses in the CWS is higher than ice storage.

4.2.3. Shifting cooling load using ice storage system and conventional chillers

Using ice storage and conventional chillers is the third method of shifting AC load which is discussed in this section. Glycol chiller is necessary for ice building during off-peak hours and conventional chiller is necessary to meet the cooling load during non-shifted period of the day.

Two options were considered under this method based on the storage capacity considered for the analysis.

- Case 05: Both peak and day cooling loads are shifted to off-peak hours
- Case 06: Only peak cooling load is shifted to off-peak hours.

In both cases only Glycol chillers are used to store energy in the off-peak hours and conventional chillers are used to meet the cooling load during non-shifted period. Heat exchanger is used to separate Glycol loop and chilled water loop as shown in the Figure 19.

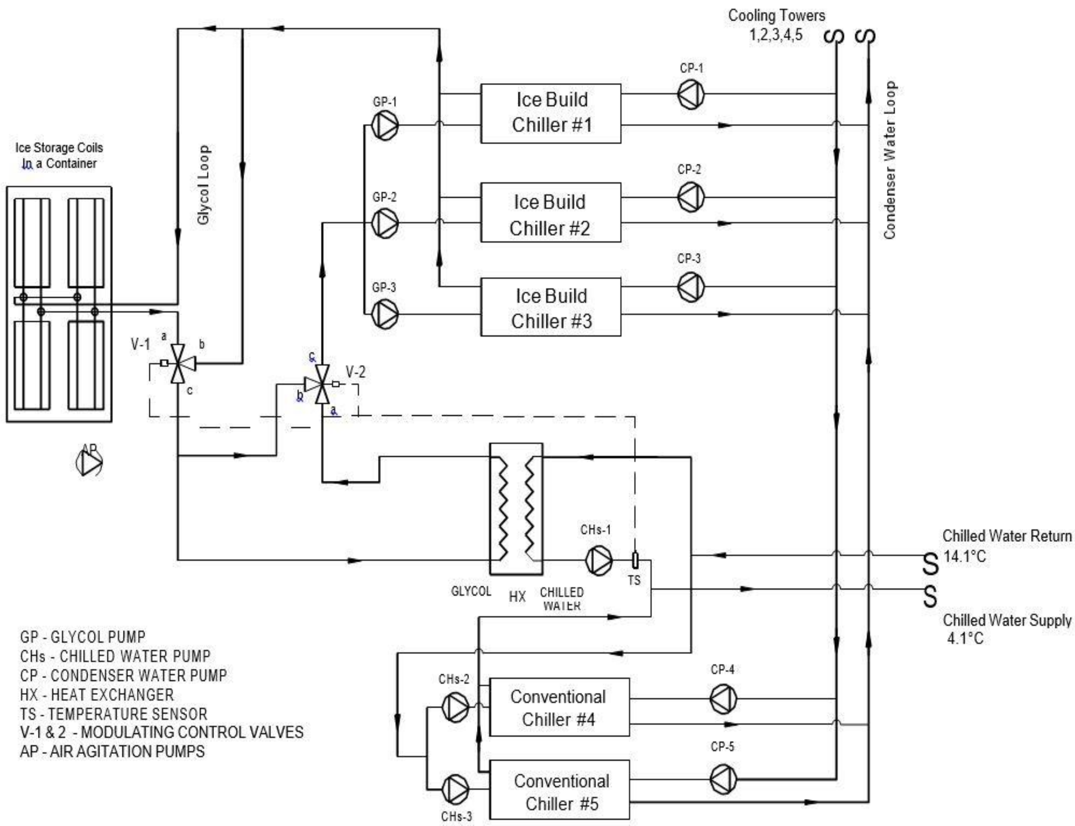

Figure 19: Ice Storage System with Glycol Chillers and Convectional Chillers [6]

4.2.3.1. Case 05: Shifting both peak and day cooling loads

In this case shifting of both peak and day cooling loads to off-peak hours using ice storage system is analyzed. Glycol chiller is used only for ice making purpose and conventional chiller is used to meet the cooling load during off-peak hours. Total peak and day cooling load of 6,403.7 TRh should be stored during off-peak hours.

Glycol chiller of 923.96 TR (735.4 kW_e) and conventional chiller of 241.20 TR (149.9 kW_e) are required for the proposed case 05. Total electrical energy consumption of the chillers are 6,248.1 kWh_e which is 1,221.1 kWh_e higher than the existing HVAC system of the hotel. This is mainly due to low COP of Glycol chillers and losses in the ice storage system and heat exchanger. Figure 20 shows the load profile of existing and proposed case with ice storage.

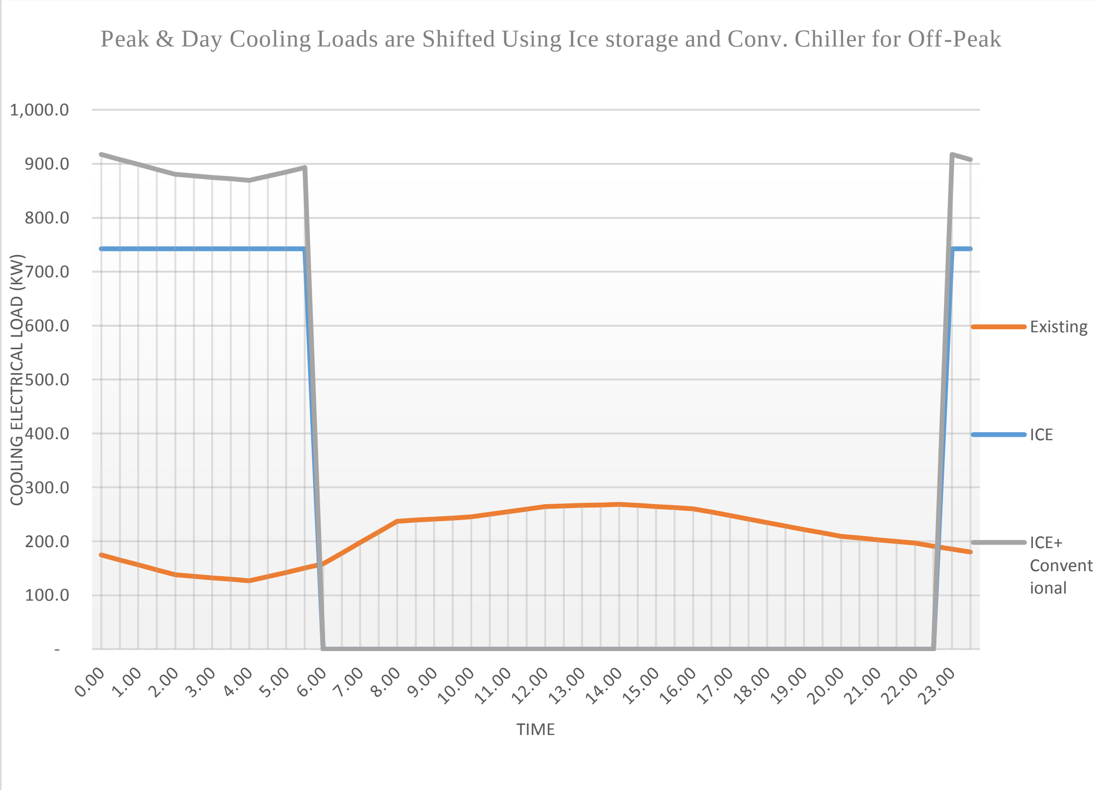

Figure 20: Load Profile of Chiller Shifting Peak and Day using Ice Storage and Convectional Chiller

Case 05 required five numbers of 300 TR cooling towers. Existing system has two 300 TR cooling towers, hence three 300 TR cooling towers were added to the existing HVAC system. Cooling towers are operated only in off-peak hours and total energy consumption of the cooling towers are 262.5 kWh_e which is 97.5 kWh_e less than the existing system.

Total energy consumption is 6,510.6 kWh_e.

4.2.3.2. Case 06: Shifting only peak cooling load

In this case shifting only peak cooling load to off-peak hours using ice storage system is analyzed. Glycol chiller is only used for ice making and conventional chiller is used to meet the cooling load during day and off-peak hours. Total peak cooling load of 1,322.0 TRh should be stored during off-peak hours.

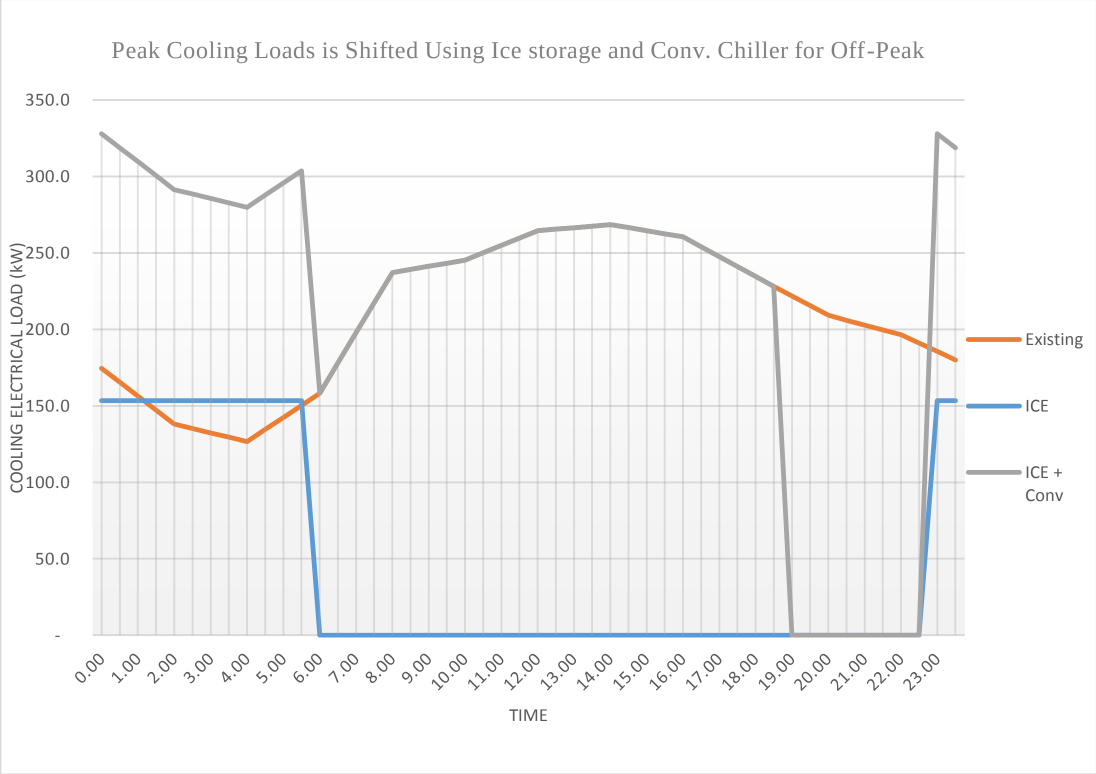

Figure 21: Load Profile of Chiller Shifting Only Peak using Ice Storage and Convectional Chiller

Glycol chiller of 190.74 TR (151.8 kW_e) and conventional chiller of 390.90 TR (242.8 kW_e) are required for the proposed case 06. Total electrical energy consumption of the chillers are 5,279.2 kWh_e which is 252.1 kWh_e higher than the existing HVAC system of the hotel. This is mainly due to low COP of Glycol chillers and losses in the ice storage system and Heat exchanger. Figure 21 shows the load profile of existing and proposed case with ice storage.

Case 06 required two numbers of 300 TR cooling towers. Existing system has two 300 TR cooling towers. Hence, additional cooling towers were not required. Cooling towers are operated in day and off-peak hours only. Total energy consumption of the cooling towers are 300.0 kWh_e which is 60 kWh_e less than the existing system.

The total energy consumption for case 06 is 5,579.2 kWh_e.

4.2.3.3. Modifications to the existing system

- Heat exchanger is added to the system to separate Glycol loop and Chilled water loop.
- Cooling Towers will be added to the System based on the chiller capacities of each case (Case 05 & Case 06)
- Two pumps were required for addition of new chillers to the system based on the required chiller capacities for each case (Case 05 & Case 06).

4.2.3.4. Advantages

- Required chiller capacities are small compared to case 01 and case 02.
- Energy consumption is lower compared to case 01 and case 02.
- Can use existing conventional chiller.

4.2.3.5. Disadvantages

- COP of Glycol chillers are much lower compared with the conventional chillers. Therefore energy consumption of Glycol chillers are higher for the same cooling load.
- Need heat exchanger to separate Glycol loop and chilled water loop which will increase the investment.
- Required two type of chillers which will increase the investment and increase the complexity of the operation.

4.3. Storage Calculation

Storage required to shift peak and day cooling load to off-peak is 6,403.7 TRh and to shift peak cooling load to off-peak is 1,322.0 TRh. Equations 4.1 is used to calculate the required storage capacity for chilled water and Equation 4.2 is used to calculate the required storage capacity for ice storage.

- For ice storage systems

$$V = \frac{X * 12{,}000\ \text{Btu/Tonhours}}{L * SG * eff * 1000} * 0.454\ \text{kg/lb} \qquad [2] \qquad (4.1)$$

- V = TES tank volume, m^3
- X = amount of thermal capacity required, ton-h
- L = Latent heat of fusion of ice, Btu/lb
- SG = Specific Gravity
- eff = storage efficiency, typically 0.99

- For chilled water storage systems

$$V = \frac{X * 12{,}000\ Btu/Tonhours}{Cp * \Delta T * SG * eff * 1000} * 0.454\ kg/lb \qquad [2] \qquad (4.2)$$

- V = TES tank volume, m^3
- X = amount of thermal capacity required, ton-h
- ΔT = temperature difference, °C
- C_P = specific heat of water, Btu/lb·°c
- SG = specific gravity
- eff = storage efficiency, typically 0.90

4.4. Summary of the Technical Evaluation

Table 7 shows the summary of the six cases analyzed in this section.

Table 7: Summery Of the Technical Evaluation

	Energy Consumption (kWhe)			Storage Volume (m^3)
	Chillers	Cooling Towers	Total	
Case 01	6,556.5	262.5	6,819.0	285.57
Case 02	6,515.6	300.0	6,815.6	58.95
Case 03	5,424.9	262.5	5,687.4	832.48
Case 04	5,109.2	300.0	5,409.2	171.86
Case 05	6,248.1	262.5	6,510.6	285.57
Case 06	5,279.2	300.0	5,579.2	58.95

Shifting of peak cooling load reduces average demand of 205 kW from the peak period and shifting of day will reduce average demand of 242 kW from day period of the utility.

5. FINANCIAL ANALYSIS

In this chapter financial evaluation is carried out to identify the viability of six cases analyzed in the Chapter 4. It is intended to identify the benefit to the customer, the utility and to the society. For the financial evaluation, it is required to identify the cost on the investment for each case analyzed in Chapter 4 and identify the potential benefits it will derive.

5.1. Investment Cost

The cost of HVAC equipment identified in Chapter 4 for the modification of existing system is given in Table 8.

Table 8: Cost of HVAC Equipment (Year 2017)

Item	Capacity		Price (LKR)
Glycol Chiller	200	TR	13,500,000.00
Glycol Chiller	300	TR	22,000,000.00
Conventional Chiller	100	TR	7,500,000.00
Conventional Chiller	150	TR	10,500,000.00
Conventional Chiller	200	TR	13,000,000.00
Conventional Chiller	300	TR	18,000,000.00
Conventional Chiller	450	TR	26,000,000.00
Ice Storage	250	TRh	2,225,000.00
Chilled Water S	1	m^3	55,000.00
Heat Exchanger	200	RT	2,150,000.00
Heat Exchanger	420	RT	3,635,000.00
Cooling Tower	350	TR	2,200,000.00
Pumps	1		500,000.00
Pipe work	1	m	10,000.00
Insulation	1	m^3	3,600.00

Source: Shin Nippon Lanka (Pvt) Ltd and Abans Engineering (Pvt) Ltd

5.2. Benefits to the Industry

The customers will be benefited through shifting their peak time energy usage to off-peak period due to the TOU tariff offered by the CEB.

$$\text{Benefit to the Industry} = (\text{Energy cost of existing system}) - (\text{Energy cost of proposed system})$$

In order to evaluate the viability of the investment, simple payback period for the investment and project IRR was calculated.

$$\text{Simple Payback Period} = \frac{\text{Investment Cost}}{\text{Savings per year}}$$

For calculating the IRR following parameters were considered.

- Project life time 20 years
- Reselling value after 20 years 40% (for chillers only)
- Debt: Equity ratio 70:30
- Loan period 07 years
- Loan interest 16%

5.3. Benefits to the Utility

Benefits to the utility can be calculated using avoided cost method. Energy cost saving to the utility by shifting peak and day energy to off-peak period can be calculated. Reduction of energy in peak and day is from high cost thermal power plants. Energy reduction in peak period is considered to be reduced from GT 7 in Kelanithissa Power Station and reduction in the day period is considered to be from AES Kelanithissa Power Station. Energy increase in the off-peak period due to shifted load is considered to be from Norochchole Power station.

Unit cost of power stations considered for the above analysis is given in the Table 9.

Table 9: Unit Cost of Power Plant

Power Plant	Unit Cost (LKR/kWh)
GT7	47.56
AES	22.45
Norochchole	7.32

The benefits gained from shifting AC load to the Utility is not only limited to avoided cost on power generation. There are many other benefits which were not considered into the calculation, but will benefit the Utility. Some of the benefits are,

- Delay in the investment costs on new power plants that will be required if demand is not reduced.
- Delay the investment on transmission and distribution upgrades.
- Efficiency improvement of the coal power plants during the off peak time interval through the increased demand.
- Increase in the system stability.

5.4. Operating Cost of Existing System

Energy consumption of chiller and cooling towers are considered when calculating the operating cost of existing system as they are the main components to be replaced when implementing the TES. Other components of HVAC system will remain the same. Therefore, to calculate operating cost of existing system only chiller and cooling towers are considered as they are the components to be changed in proposed systems.

Operating cost of the existing system per day is given in the Table 10 and 11.

Table 10: Per day Operation Cost of the Chiller

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	1,048.9	8.80	9,230.22
Day	3,156.9	13.70	43,250.00
Peak	821.3	22.50	18,478.45
Total	5,027.1		70,958.66

Table 11: Per Day Operation Cost of the Cooling Tower

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	105	8.8	924.00
Day	195	13.7	2,671.50
Peak	60	22.5	1,350.00
Total	360		4,945.50

Total Chiller and Cooling Tower power consumption of the existing system is 5,387.1 kWh_e and per day operation cost is LKR 75,904.16.

5.5. Operating Cost for Proposed Cases

In this section operating cost is calculated for each proposed case (case 01 to case 06) analyzed in Chapter 4 and compared with the existing HVAC system to calculate the economic benefit to the hotel industry.

5.5.1. Case 01: Shifting both peak and day loads using only Glycol chillers

Shifting of both Peak and day cooling load using ice storage system and Glycol chillers only. Required storage, chillers and cooling tower capacities are given below.

Required Storage Capacity = 6,403.7 TRh

Required Glycol Chiller Capacity = 1,176.8 TR (936.6 kW_e)

Required Cooling Towers = 5 Nos. of 300 TR cooling towers.

Operating cost of proposed system per day is given in Table 12 and Table 13.

Table 12: Per day Operation Cost of the Chiller in Case 01

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	6,556.5	8.80	57,697.04
Day		13.70	-
Peak		22.50	-
Total	6,556.5		57,697.04

Table 13: Per day Operation Cost of the Cooling Tower Case 01

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	262.5	8.8	2,310.00
Day	0	13.7	0.00
Peak	0	22.5	0.00
Total	262.5		2,310.00

Operating cost of the proposed system is LKR 60,007.04 per day and when compared with existing system LKR 15,897.12 can be saved. Total savings per year is LKR 5,802,448.32 and required ice storage capacity is 285.57 m^3.

Investment for the case 01 is given in the Table 14.

Table 14: Total Investment of Case 01

	Unit Capacity	Unit Price (LKR)	No of Units	Total Cost (LKR)
Chiller	300 TR	22,000,000	4	88,000,000
ICS	250 TRh	2,225,000	8	62,300,000
Heat Exchanger	420 TR	3,635,000	3	10,905,000
Cooling Towers	300 TR	2,200,000	3	6,600,000
Pumps and Valves		500,000	8	4,000,000
Valves		75,000	3	225,000
Pipe Work		10,000	120	1,200,000
Insulation		3,600	80	288,000
Total Investment				173,518,000

Simple payback period for case 01 is 29.9 years and project IRR is -0.2%. With long payback period and negative IRR, project is not viable. Therefore case 01 is not recommended to invest.

Due to increase of the chiller and cooling tower capacities, it is required to upgrade the capacity of power transformer and cable sizes in hotel electrical system. This will increase the total investment and make this case further un-attractive.

5.5.2. Case 02: Shifting only peak load using only Glycol chillers

Shifting only peak cooling load using ice storage system with Glycol chillers only. Required storage, chillers and cooling tower capacities are given below.

Required Storage Capacity = 1,322 TRh

Required Glycol Chiller Capacity = 436.3 TR (347.2 kW_e)

Required Cooling Towers = 2 Nos. of 300 TR cooling towers.

Operating cost of proposed system per day is given in Table 15 and Table 16.

Table 15: Per day Operation Cost of the Chiller in Case 02

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	2,430.59	8.8	21,389.17
Day	4,085.04	13.7	55,965.10
Peak	-	22.5	-
Total	6,515.63		77,354.27

Table 16: Per day Operation Cost of the Cooling Tower Case 02

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	105	8.8	924.00
Day	195	13.7	2,671.50
Peak	0	22.5	0.00
Total	300		3,595.50

Operating cost of the proposed system is LKR 80,949.77 per day and it is LKR 5,045.61 higher than the existing system. Therefore no saving can be expected from this case. Hence this case is not further studied.

5.5.3. Case 03: Shifting both peak and day loads using CWS

Shifting of peak and day cooling loads using a chilled water storage system. Required storage, chillers and cooling tower capacities are given below.

Required Storage Capacity = 6,403.7 TRh

Required Glycol Chiller Capacity = 1,247.49 TR (775 kW_e)

Required Cooling Towers = 5 Nos. of 300 TR cooling towers.

Electricity consumption is lower compared to the case 01 even the required chiller capacity is higher. This is due to the high COP in conventional chillers compared to the Glycol chillers.

Operating cost of proposed system per day is given in Table 17 and Table 18.

Table 17: Per day Operation Cost of the Chiller in Case 03

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	5,424.9	8.80	47,739.18
Day	-	13.70	-
Peak	-	22.50	-
Total	5,424.9		47,739.18

Table 18: Per day Operation Cost of the Cooling Tower Case 03

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	262.5	8.8	2,310.00
Day	0	13.7	0.00
Peak	0	22.5	0.00
Total	262.5		2,310.00

Operating cost of the proposed system is LKR 50,049.18 per day and when compared with existing system LKR 25,854.98 can be saved. Total savings per year is LKR 9,437,068.86 and required chilled water storage capacity is 832.48m^3.

Investment for the case 03 is given in the Table 19.

Table 19: Total Investment of Case 03

	Unit Capacity	Unit Price (LKR)	No of Units	Total Cost (LKR)
Chiller	300 TR	26,000,000	2	52,000,000
CWS	$1m^3$	55,000	833	45,815,000
Cooling Towers	300 TR	2,200,000	3	6,600,000
Pumps		500,000	2	1,000,000
Valves		75,000	3	225,000
Pipe Work		10,000	60	600,000
Insulation		3,600	60	216,000
Total Investment				**106,456,000**

Simple payback period for case 03 is 11.3 years and project IRR is 6.8% which is comparatively better than case 01 but still project is not viable due to low IRR. Therefore case 03 is not recommended to be implemented and it will not attract investors due to high payback period and low project IRR.

Due to increase of the chiller and cooling tower capacities, it is required to upgrade the capacity of power transformer and cable sizes in hotel electrical system. This will increase the total investment and make this case further un-attractive.

5.5.4. Case 04: Shifting only peak load using CWS

Shifting only peak cooling load using a chilled water storage system. Required storage, chillers and cooling tower capacities are given below.

Required Storage Capacity = 1,322 TRh

Required Glycol Chiller Capacity = 448.9 TR (278.9 kW_e)

Required Cooling Towers = 2 Nos. of 300 TR cooling towers.

Electricity consumption is lower compared to the case 02 even the required chiller capacity is higher. This is due to the high COP in conventional chillers compared to the Glycol chillers.

Operating cost of proposed system per day is given in Table 20 and Table 21.

Table 20: Per day Operation Cost of the Chiller in Case 04

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	1,952.3	8.80	17,180.05
Day	3,156.9	13.70	43,250.00
Peak	-	22.50	-
Total	5,109.2		60,430.05

Table 21: Per day Operation Cost of the Cooling Tower Case 04

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	105	8.8	924.00
Day	195	13.7	2,671.50
Peak	0	22.5	0.00
Total	300		3,595.50

Operating cost of the proposed system is LKR 65,375.55 per day and when compared with existing system LKR 14,124.11 can be saved. Total savings per year is LKR 4,335,691.93 and required chilled water storage capacity is 171.86m^3.

Investment for the case 04 is given in the Table 22.

Table 22: Total Investment of Case 04

	Unit Capacity	Unit Price (LKR)	No of Units	Total Cost (LKR)
CWS	1m^3	55,000	180	9,900,000
Valves		75,000	3	225,000
Pipe Work		10,000	30	300,000
Insulation		3,600	30	108,000
Total Investment				**10,533,000**

Simple payback period for case 04 is 2.4 years and project IRR is 40.8% which is a very good project compared to the other cases. Therefore case 04 is recommended for implementation.

In this case it is not required to upgrade the electrical system of the hotel, as capacity of the required chiller is lower than that of the existing chiller at the hotel.

5.5.5. Case 05: Shifting both peak and day loads using ice storage system

Shifting peak and day cooling load using ice storage system and conventional chiller to meet the off-peak cooling load. Required storage, chiller and cooling tower capacities are given below.

Required Storage Capacity = 6,403.7 TRh
Required Glycol Chiller Capacity = 924 TR (735.4 kW_e)
Required Conventional Chiller Capacity = 241.2 TR (149.8 kW_e)
Required Cooling Towers = 5 Nos. of 300 TR cooling towers.

Operating cost of proposed system per day is given in Table 23 and Table 24.

Table 23: Per day Operation Cost of the Chiller in Case 05

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	6,248.1	8.80	54,983.44
Day	-	13.70	-
Peak	-	22.50	-
Total	6,248.1		54,983.44

Table 24: Per day Operation Cost of the Cooling Tower Case 05

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	262.5	8.8	2,310.00
Day	0	13.7	0.00
Peak	0	22.5	0.00
Total	262.5		2,310.00

Operating cost of the proposed system is LKR 57,293.44 per day and when compared with existing system LKR 18,610.72 can be saved. Total savings per year is LKR 6,792,912.14 and required ice storage capacity is 285.57m^3.

Investment for the case 05 is given in the Table 25.

Table 25: Total Investment of Case 05

	Unit Capacity	Unit Price (LKR)	No of Units	Total Cost (LKR)
Chiller	300 TR	22,000,000	3	66,000,000
ICS	250 TRh	2,225,000	28	62,300,000
Heat Exchanger	420 TR	3,635,000	2	7,270,000
Cooling Towers	300 TR	2,200,000	3	6,600,000
Pumps and Valves		500,000	6	3,000,000
Valves		75,000	3	225,000
Pipe Work		10,000	80	800,000
Insulation		3,600	80	288,000
Total Investment				**146,483,000**

Simple payback period for case 05 is 21.6 years and project IRR is 1.5% which is not a viable project. Therefore case 05 is not recommended to be implemented and it will not attract investors.

Due to increase of the chiller and cooling tower capacities, it is required to upgrade the capacity of power transformer and cable sizes in hotel electrical system. This will increase the total investment and make this case further un-attractive.

5.5.6. Case 06: Shifting only peak load using ice storage system

Shifting of only peak cooling load is proposed by using an ice storage system and conventional chiller to meet the off-peak and Day cooling load. Required storage, chiller and cooling tower capacities are given below.

Required Storage Capacity = 1,322 TRh

Required Glycol Chiller Capacity = 190.7 TR (151.8 kW_e)

Required Conventional Chiller Capacity = 390.9 TR (242.8 kW_e)

Required Cooling Towers = 2 Nos. of 300 TR cooling towers.

Operating cost of proposed system per day is given in Table 26 and Table 27.

Table 26: Per day Operation Cost of the Chiller in Case 06

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
off peak	2,122.2	8.80	18,675.57
Day	3,156.9	13.70	43,250.00
Peak	-	22.50	-
Total	5,279.2		61,925.57

Table 27: Per day Operation Cost of the Cooling Tower Case 06

TOU	Energy (kWh)	Tariff (LKR/kWh)	Cost (LKR)
Off Peak	105	8.8	924.00
Day	195	13.7	2,671.50
Peak	0	22.5	0.00
Total	300		3,595.50

Operating cost of the proposed system is LKR 65,521.07 per day and when compared with existing system LKR 10,383.09 can be saved. Total savings per year is LKR 3,789,828.89 and required ice storage capacity is 58.95m^3.

Investment for the case 06 is given in the Table 28.

Table 28: Total Investment of Case 06

	Unit Capacity	Unit Price (LKR)	No of Units	Total Cost (LKR)
Chiller	300 TR	13,500,000	1	13,500,000
ICS	250 TRh	2,225,000	6	13,350,000
Heat Exchanger	420 TR	2,150,000	1	2,150,000
Pumps and Valves		500,000	2	1,000,000
Valves		150,000	2	300,000
Pipe Work		10,000	30	300,000
Insulation		3,600	30	108,000
Total Investment				**30,708,000**

Simple payback period for case 06 is 8.1 years and project IRR is 10.8% which is not a viable project. Therefore case 06 is not recommended to be implemented and it will not attract investors.

Due to increase of the chiller and cooling tower capacities, it is required to upgrade the capacity of power transformer and cable sizes in hotel electrical system. This will increase the total investment and make this case further un-attractive.

5.6. Summary

Table 29 shows the summary of financial analysis done for six cases identified in Chapter 4.

Table 29: Summery of the Financial Analysis

	Savings Per Year (LKR)	Storage Volume (m^3)	Simple Pay back	Project IRR
Case 01	5,802,448.32	285.57	29.90	(0.21%)
Case 02	(1,841,648.96)	58.95	-	-
Case 03	9,437,068.86	832.48	11.28	6.78%
Case 04	4,335,691.93	171.86	2.43	40.76%
Case 05	6,792,912.14	285.57	21.56	1.52%
Case 06	3,789,828.89	58.95	8.10	10.78%

Case 04, shifting only peak cooling load using CWS is the only viable project. If space is limited for the storage facility case 06 can be considered with low Return on Investment. Calculating the other benefits such as energy reduction in pumps and fan coil units in ice storage systems will give an attractive simple payback and project IRR for case 6 as well.

5.7. Utility Benefits

In each case there is a benefit to the utility (CEB) from the reduction of peak and day load. Utility benefit can be calculated using the generation cost figures given in the Table 9 and the method suggested under 5.44. In addition to that utility will be benefited of reducing its peak demand from 205 kW in every case.

Table 30 shows the benefit calculated for the utility for each case analyzed in the Chapter 4 and Chapter 5.

Table 30 : Benefit to the Utility

	Savings per year (LKR)
Case 1	26,245,868.23
Case 2	11,401,561.34
Case 3	28,444,736.78
Case 4	11,855,498.52
Case 5	26,245,868.23
Case 6	11,401,561.34

Table 31 show the project IRR calculated from utility side for each case analyzed in Chapter 4 and Chapter 5.

Table 31: Calculate Project IRR from Utility side

	Savings Per Year (LKR)	Simple Pay back	Project IRR
Case 01	26,245,868.23	6.61	13.85%
Case 02	-	-	-
Case 03	28,444,736.78	3.74	26.05%
Case 04	11,855,498.52	0.89	112.50%
Case 05	26,245,868.23	5.58	16.86%
Case 06	11,401,561.34	2.69	36.67%

6. CONCLUSIONS AND RECOMMENDATIONS

Results obtained in Chapter 5 on the cost benefit analysis of the investments were studied and reached on the following conclusions.

6.1. Conclusions

Six cases were analyzed in Chapter 4 and Chapter 5 to identify the best TES system for the Cinnamon Lakeside Hotel. Results of the analysis show that chilled water storage system is the best TES system for the existing HVAC systems. CWS system gives the lowest simple payback period and highest IRR compared with ice storage systems. Existing conventional chiller can be used with CWS and few modifications are required compared to the ice storage systems. Therefore total investment is lower than ice storage system for the same storage capacity.

Two cases were analyzed with CWS and shifting only the peak cooling load to off-peak hours is the best TES solution for the Cinnamon Lakeside Hotel because no additional chillers are required. Space limitations should also be considered when selecting a TES system. Shifting only peak cooling load to off-peak also requires less storage capacity compared to shifting both peak and day cooling loads.

Results of the financial evaluation in Chapter 5 give simple payback of 2.43 years and project IRR of 40.76% for case 04 which are good financial indicators for a project. These figures will attract investors on TES shifting peak cooling load to off-peak hours using CWS system.

Ice storage systems can increase the temperature difference between return water and chilled water. This will reduce the chilled water flow rate required to meet the cooling load of the building. Reduction of the chilled water flow rate will reduce the pump and fan motor sizes which reduce the energy consumption and investment of the HVAC system. Ice storage system will also reduce the duct sizes and pipe sizes due to high temperature difference achieved between chilled water and return water which will reduce the investment cost of infrastructure.

If ice storage system was implemented at the construction stage of the hotel, investment on HVAC system would be lower due to the reduction of equipment, duct work and pipe diameter sizes. This would also reduce the total energy consumption of HVAC system due to reduction of equipment sizes. Implementing of the ice storage system at the initial stage of construction could give high project IRR for cases 05 and 06 which would attract investors.

Shifting only peak cooling load to off-peak hours will reduce the utility peak demand by 205 kW and calculated saving by using the method suggested in section 5.3 is around 11.4 Million Sri Lankan Rupees. If this can be projected to 50 similar capacity buildings utility can achieve 10 MW peak savings.

In addition to the above financial benefits storage techniques will reduce the gap between the peak and off-peak demand. Smoothing the load curve will reduce the requirement of high cost thermal power plants for a shorter period which will reduce the total generation cost of the system and improve the efficiency of base load power plants by allowing them to operate at full load even in the off-peak period.

Storage techniques will also reduce the costs incurred as a country on crude oil imports.

6.2. Problems and Limitations

For this study energy consumption of only chiller and cooling towers of Cinnamon Lakeside Hotel were considered. It was assumed that energy consumption of fan and pump motors would remain the in both existing and proposed cases.

Using ice storage will lower the energy consumption of fan and pump motors which will increase the savings to the industry as well as to the utility. Therefore calculated simple payback period and project IRR can be much improved for case 05 and case 06 in practical situation.

6.3. Recommendation

This study concluded that Thermal Energy Storage is a good DSM option for hotel industry in Sri Lanka with the present TOU tariff structure. It was recommended to analyze this in more detail to identify the total benefit it will derive in practical situation.

It is recommended that all the large hotels in Sri Lanka should be encouraged using Chilled Water Storage in order to shift their AC load from peak to off peak hours.

Case 04 and Case 06 can be implemented as pilot projects to identify the practical viability and problems associated with it.

7. REFERENCES

[1] Long term generation expansion plan 2015-2034, Ceylon Electricity Board.

[2] Thermal storage, Chap.51, in ASHRAE Handbook—HVAC Systems and Equipment, 2012.

[3] Thermal storage, Chap.34, ASHRAE Handbook, HVAC Applications, SI Edition, Supported by ASHRAE Research, 2003

[4] Federal Energy Management Program "Thermal Energy Storage for Space Cooling", December 2000.

[5] Hashem Akbari and Atila Mertol, "Thermal Energy Storage for Cooling of Commercial Buildings", NATO Advanced Study Institute on Energy Storage Systems' Fundamentals & Applications, Izmir, Turkey, June 27-July 8, 1988.

[6] Thermal Ice Storage, Application and Design Guid, Evapco, INC, 2007.

[7] Ensuring Sustainability in Sri Lanka's Growing Hotel Industry by International finance group, World Bank 2013.

[8] Decision on Transmission and Bulk Supply Tariffs, Public Utilities Commission of Sri Lanka, Effective from 1st April 2017.

[9] Marylynn Placet, Srinivas Katipamula, Bing Liu, James Dirks, and Yulong Xie, "Energy End-Use Patterns in Full-Service Hotels: A Case Study"

[10] Chandana Dalugoda, Rahula Attalage, "Evaluating benefits of using ice thermal storage in mechanical cooling systems in Sri Lanka"

[11] G.Y.Fang, H.Li, "Economic Analysis of Cool Storage Air-Conditioning Systems" International Journal on Architectural Science, Volume 5, Number2, p.47-51, 2004

[12] Kunfeng Liang, Xianle Ren, Chunlei Ruan and Lin Wang, "Operation Modes and Energy Analysis of a New Ice-Storage Air-Conditioning System", The Open Electircal & Electronic Engineering Journal, 2015, 9, 7-14.

[13] E.A.E.H. Hemachandra, “Potential for Promotion of Demand Side Management Through A Market Based Approach”, M.Sc., Dep. of Elec. Eng., University of Moratuwa, Sri Lanka, May 2016.

[14] Kristoper L. Kinney, Eng. Lock Lee, “A Showcase for Energy Efficient Hotels in South Asia”.

[15] William P. Bahnfleth, Ph.D., P.E., Graeme R. McLeod, Steven L. Bowins, “Chilled Water Storage in Western Australia”.

[16] Design and Construction of an Ice-in-Tank Diurnal Ice Storage Cooling System for the PX building at Fort Stewart, GA by Chang W. Sohn, John Tomlinson, July 1988.