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Analysis of ice cool thermal storage for a clinic building in Kuwait

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Abstract

In Kuwait Air Conditioning systems (AC) consume 61% and 40% of the peak electrical load and total electrical energy respectively. This is due to a very high ambient temperature for long summer period extended from April to October and low energy cost. This paper gives an overview of the electrical peak and energy consumption in Kuwait, and it has been found that the average increase in annual peak electrical demand, and energy consumption for year 1998 to 2002 was 6.2% and 6.4% respectively. One method of reducing the peak electrical demand of AC systems during the day period is by incorporating an Ice Cool Thermal Storage (ICTS) with the AC system. A clinic building has been selected to study the effect of using ICTS with different operation strategies such as partial (load levelling), partial (demand limiting), and full storage operations on chiller and storage sizes, reduction of peak electrical demand, and energy consumption of the chiller for selected charging and discharging hours. It has been found that the full storage operation has the largest chiller and storage capacities, energy consumption and peak electrical reduction. However, partial storage (load levelling) has the smallest chiller and storage capacities, and peak electrical reduction. This paper also provides a detailed comparison of using ICTS operating strategies with AC and AC systems without ICTS.

Keywords: cool thermal storage; peak power; energy consumption; Kuwait

1. Peak electrical load and electricity consumption in Kuwait

In July 2003, the Water and Electricity Ministries of Kuwait were merged, along with the Oil Ministry, into a new Energy Ministry. The new Ministry is in charge of power and water provision, management and operation of power plants, and general policy for the Kuwaiti energy sector.

Kuwait has five fossil fuelled power stations (Doha East, Doha West, al-Subiya, Shuaiba South, and al-Zour South) and a total electrical generation capacity of about 9.27 GW, the percentage contribution of electrical peak load for individual power stations is given in Figure 1 [1].

The generated fossil fuelled energy consumption has increased in recent years due to the heavy use of Air Conditioning AC system, reliance on desalination for water, and highly subsidised electricity and water prices.

The peak load as a percentage of installed capacity for years 1998 to 2002 is shown in Figure 2 [1]. This is an important figure since it gives the country information about when new power plants must be built. The higher percentage of the peak electrical load to the total installed capacity of the five stations means the country must invest to build new power plants to cope with the increase in the electrical peak demand.

In Figure 2 [1], the percentage of peak load to the installed capacity decreased from 77.4% in year 1998 to 70.2% in year 2000, because in April 1998 Subiya power plant was partially commissioned at a cost of around $2.2 billion, and in year 2000 the power plant operated at full load with 2400 MW total capacity, hence increasing the total installed power generation of the country.

In year 2002 the percentage again increased to 78.8% which means the Ministry of Energy must build or expand existing power plants to cope with the increase in future electrical demand.

Figures 3 and 4 show the percentage increase in annual peak electricity load and electrical energy consumption for years 1998 up to 2002 respectively. The highest percentage increase in the annual peak electricity load is 8.2% for year 1998, the same year has also the highest percentage increase in the annual electrical energy of 9.0%. Years 1998 to 2002, the average increase in the annual electrical peak demand and electrical energy consumption is approximately 6.2% and 6.4% respectively.

The maximum electrical load in MW for each month for the year 2002 is shown in Figure 5 [1]. The maximum electrical load occurs in July with 7250 MW and a minimum of 3160 MW in February. The peak load in July represents about 78.2% of the total installed capacity of the country of that year. The high demand in electrical load during this month, and the other hot months extending from April to October is mainly due to the high ambient temperature, which sometimes reaches 50°C. This increases the power consumption of the AC systems, which represent around 61% of the peak electrical power generation at the peak month, and 40% of the total annual electrical energy generation of the country. The operation of AC systems in these hot and humid months is essential to maintain comfort living and working conditions for people in the buildings.

In the winter season (December, January, and February), when the dry bulb temperature ranges between 15°C to 25°C for most days, the AC systems for all residential building which use package AC systems are off. However, in some large commercial, institutional, and governmental buildings the AC systems are in operation around the year, and because of the low dry bulb temperature at these months most of the AC systems are partially operating or they are operating at part load which results in low electrical power consumption.

Figure 6 illustrates electrical energy consumption for each month of the year 2002 in GWh [1]. Again the electrical generation is high during the summer period because of the high demand in AC systems. The highest electrical energy consumed was in July with 389.6 GWh. There is no reliable reason why the energy consumption at the months of October, November, and December are still high, comparing with months such as January up to April. The only possible explanation of this increase in electrical consumption is due to the commission of new buildings, desalination plants, and higher water consumption [2] in the country during the end months of year 2002.

An hourly electrical generation in MW for the peak day in year 2002 is shown in Figure 7 [1]. The peak electrical demand of the day occurs between 3:00pm and 4:00pm and is about 7250 MW, the maximum recorded dry bulb temperature at the peak load was 50°C with relative humidity of 7%. The lowest demand occurs at 6:00am with a demand of 5780 MW. The power demand rises gradually from a minimum at 6:00am until 4:00pm due to the increase in dry bulb temperature and therefore, power consumption of the AC systems for most of the building. After 4:00pm the power falls until 7:00pm and then increases slightly at 7:00pm because the lighting in buildings and streets are usually switched on at this time.

Kuwait's per capita electricity consumption is ranked number seven in the world [3], per capita consumption of electrical energy in the year 2002 was 12832 kWh per year and 35.2 kWh per day [1]. Overall, Kuwaiti power demand has been growing rapidly in recent years, and is expected to continue increasing at a 7%-9% rate in coming years, necessitating construction of new generating capacity.

Kuwait has some of the lowest power prices in the world and the government may reduce subsidies to try to cut its present electricity use. At present all tariffs for domestic customers are straight-line tariffs. Electricity cost 2 fils per kWh (approximately 6.5 cents US), while water costs 800 fils for 3.78 m^3 (approximately $2.6 US). The actual cost of the electricity production is estimated to be 20 fils (approximately 65 cents US) which means that electricity users in Kuwait pay only 10% of the actual electricity cost.

The Ministry Of Energy (MOE) also charges for cable connection to a building, the user pays only $169 US per kW, however the actual cost of cable connection for the

MOE is estimated to be around $1356 US per kW. In fact the cost of the cable connection is higher than this, because this cost represents only the cost of the power plants, transmission, and distribution and excludes fuel and labour costs. The cable connection requires a current capacity sufficient to feed power to a user up to the maximum power drawn from the utilities for operation of the cooling system.

Since the growth of additional power plants is directly linked to the maximum power demand of AC systems, and peak power demand of the national utilities coincides with the maximum power demand of AC systems, Thermal Energy Storage (TES) is one method which can be applied to reduce the peak power demand of the AC systems in Kuwait and hence reduce the electricity demand at peak day hours.

TES is one of the most preferred technologies for shifting cooling electrical demand from peak daytime to night hours. The feasibility of incorporating TES into conventional Heating Ventilation and Air Conditioning (HVAC) systems has been studied in [4]. The economics, energy saving, design consideration, and impact on the environment are well discussed in [5].

In this paper the application of using ICTS for Kuwait typical design day conditions is presented. A clinic building was selected to study the impact of incorporating ICTS in order to reduce peak electrical power during the day. Also this paper compares chiller and storage capacity sizes, and chiller energy consumption of a conventional AC system with partial load levelling, partial demand limiting, and full storage ICTS operation strategies.

2. Introduction to ICTS

ICTS is one of the cool thermal energy storage technologies that can significantly reduce the peak power demand for AC systems in the buildings of Kuwait. This can be achieved by shifting the operation of the AC system from night time to day time hours. ICTS can be considered as one of several methods for lowering energy consumption of AC systems in buildings [6]. It can also reduce the initial cost of the AC system by reducing the size of cooling production capacity equipment, such as pipes, duct, and air handling units (AHUs) [7].

Ice thermal storage utilises the latent heat of fusion for water of 335 kJ/kg to store cooling energy. The storage volume is generally in the range of 0.019 to 0.027 m^3/kWh, depending on the specific ice storage technology (i.e. Ice harvesting, external melt ice-on-coil, internal melt ice-on-coil etc).

Since ITCS stores cooling energy in ice at 0°C, the freezing point of water, the chiller must be capable of producing charging temperatures of -6°C to -3°C, below the normal operating range of conventional chillers for air conditioning. The heat transfer fluid in the ice thermal storage systems may be the refrigerant itself or a secondary coolant such as 25% or 30% ethylene glycol mixed with water.

Thousands of cool storage systems have been installed in the United States. A survey conducted for ASHRAE resulted in an estimated population of 1500–2000 systems in the early 1990s [8]. Applications cover a wide range of facility types, but most commonly are offices, schools, retail stores, places of worship, refrigerated food storage facilities, and hospitals.

Between 80% and 85% of the systems installed use one of the several kinds of ice storage. Another 10–15% use chilled water storage, with eutectic salt systems representing about 5% of the systems in the survey conducted by [8]. Based on their survey, the actual demand reduction and cost saving for ice thermal storage were 100.9% and 117.4% respectively, greatest benefits being achieved with chilled water and eutectic salt systems. It was also found that most of the ice storage systems were installed for relatively small buildings with typical energy requirements ranging from 100846 to 352 kWh, and that these had the highest cost in $/kWh compared to other storage technologies.

2.1. Operating strategies

The operating strategies of cool thermal storage systems are classified as either full storage or partial storage, referring to the amount of cooling load transferred or shifted from night periods to the day periods. Partial storage can be further classified as storage priority and chiller priority.

2.1.1. Full storage

Full storage systems are designed to meet all building cooling loads of the design day from the storage. In the full storage system, the chiller runs at its full capacity during night time period when the building load is small, at the night time the chiller charges the storage and meets the building cooling loads simultaneously. Since the full storage system meets all building cooling loads during day time period, this will result in larger and, therefore more expensive chiller and storage units compared to partial storage systems.

Full storage systems are attractive when the demand charges are high, the differential between on peak and off peak energy charges is high, and when the peak demand period is short.

2.1.2. Partial storage

Partial storage systems meet part of the cooling load from the storage and part directly from the chiller during the day time. Partial storage operating strategies can be divided into load levelling and demand limiting operations.

In a load levelling system, the chiller operates at full capacity for 24 hours of the design day. When the building cooling load is less than chiller capacity, the excess cooling is stored in the storage tank, when the load exceeds the chiller capacity, the additional cooling is supplied from the storage tank.

Load levelling operation is suitable for applications where the peak cooling load is much higher than the average load (i.e. the ratio of peak to the average load is high) and the load is high for long period. It can be designed to minimise the size and cost of both the chiller and storage tank, but it reduces electricity demand during the day time period than the full storage system.

In demand limiting systems, the chiller operates at reduced capacity during the day time. It represents the middle ground between full and load levelling partial storage where the chiller operation is reduced. The chiller in this system may be controlled to keep the billing meter at the facility below a given level. The system size and cost, and saving in energy demand fall between that for full storage and load levelling partial storage.

2.1.2.1 Storage priority and chiller priority

Storage priority and chiller priority are two basic operating strategies when the system is designed for partial storage, these operating strategies divide the load between chiller and storage. Storage priority strategy meets as much of the load as possible from the storage tank, using the chiller only when the load exceeds total stored cooling capacity of the tank. However, chiller priority strategy uses the chiller to meet as much of the load as possible. Cooling is supplied from the storage only when the load exceeds chiller capacity. Storage priority generally has a more complex control scheme and larger storage and chiller sizes than the chiller priority strategy. However, it consumes less energy [9].

3. Advantages of using ice thermal cool storage for Kuwait

A chilled water temperature of 1°C can be produced by using ICTS. Through a proper use of low temperature chilled water throughout the building a reduction in the piping and air distribution can be achieved. Other significant advantages of using low temperature chilled water are a reduction in mechanical room space, ceiling space, and electrical installation. Factors that must be considered when designing a low temperature air distribution system are discussed in [10].

Thermal energy storage can be considered as a green technology, because in most locations, the electricity at night costs less than the day due to lower temperature in the night, for many cool storage installations, energy savings are achieved by using inexpensive power at night to create and store cooling, and using the storage to cool the building during the next day.

Since AC systems with ICTS operate at full load during night time, the cost of the fuel that is needed for the power plant to produce electricity during the night will be reduced. The two main reasons are, first in the night the base load plants are much more energy efficient than day time plants, with 8335 to 8970 kJ/kW heat rates [11]. Second, line losses are less during night time because much less power is transmitted at night [12]. Furthermore, results from the study by the California Energy Commission [12] showed that for the two major California utilities, it required 10% to 30% less energy to create and deliver power during night periods.

Most HVAC engineers oversize the mechanical systems by 20% to 30% when conventional air conditioning systems are used, resulting in an increase in the initial energy costs of the system. With ICTS incorporated into the AC system, a smaller cooling production system can be installed with an extra 20% safety factor and with no additional cost.

For example, as illustrated in [13], a building had 3517 kW peak load and the designer had planned to install three 1407 kW chillers and related equipment. The ICTS system used two 1407 kW chillers and 12300 kWh of storage, which provided excess capacity if the actual load was less than the predicted load.

Many central plants have limited physical space available if additional chillers are required for installation. With ICTS, the storage tanks can be located outside the central plants, or on the roof, they can also totally or partially buried under the ground and can be stacked over each other which reduces space requirements.

4. Disadvantages of ice thermal storage

The overall energy consumption of ICTS can increase, due to the production of lower temperature chilled water during the night time. During the night time hours the chiller must cool a water-glycol solution to between -6°C to -3°C rather than produce 5°C to 7°C water temperature as for conventional AC systems. This has the effect of reducing the nominal chiller capacity by approximately 30 to 40%. However, compressor efficiency will vary only slightly because lower night time dry bulb temperatures in the case of air cooled chillers, results in cooler condenser temperatures and this will help the chillers to operate more efficiently.

When using ICTS systems, the size of the chilled water pumps is larger than the conventional systems. An extra head loss must be accounted in the pressure drop in the ice storage tanks in order to size the chilled water pumps. Based on performance data [14], an ice storage tank could have a pressure drop between 1 to 17.6 meters depending on the size and design flow rates of the ice tanks. However, this problem can be overcome by properly design the ICTS, the sizes of the pumps and pipes can be significantly reduced by designing the system with reduced flow rates that results from using a larger temperature differential in the water loop. Use of a larger temperature range, for example 10°C instead of the more traditional 5.5°C temperature range results in a reduction water flow rate and therefore reductions in the pumps and pipe sizes.

5. Existing case studies of ICTS

Low temperature air distribution ICTS was designed for a commercial office building of 16723 m^2 located in Marlboro Massachusetts [7]. After learning from other ICTS projects in the area, the building owner requested the design team to compare a hydronic loop heat pump system with a low temperature air distribution, ICTS system design.

Both HVAC systems were modelled by using an energy analysis computer software package. Building characteristics and weather data were input to predict the electrical and natural gas use. The demand analysis was carried out by taking the actual installed equipment's power ratings for the low temperature air distribution, ICTS system, and equipment ratings were used for the hydronic loop heat pump system. A summary of their analysis is given in table 1.

Another case of using ICTS for cooling was reported by [15] for a department store. An ICTS was installed for an expanded department store in Oxford Street, London. At the same time, the original cooling equipment was replaced by new screw compressor chillers. The expansion resulted in an increase in the cooling load almost double the existing capacity. The ICTS was designed to provide approximately 50% of the cooling requirement on a summer design day, so the increased cooling capacity was met without increasing the size of the chiller plant or the space required on the roof for cooling towers.

The cooling system of the store comprised of three screw chillers, each rated at 603 kW when providing chilled water at 3°C in the day time mode. In the night time (charge) mode, each chiller provided 450 kW of cooling with a nominal chilled water temperature of – 6°C. The ICTS was of the external ice melt type, providing 9300 kWh of cooling during the discharge period. The ice/water is contained within a reinforced concrete tank that was constructed on the site.

A federal office building in Chicago shifts peak demand and gains emergency cooling for computers by using an ICTS system [16]. The system stores energy in the form of ice during the night, the ice is then used to act as emergency back up cooling for computers at the Harold Washington Building on Madison St. in Chicago. The existing four storage water tanks of 31.8 m^3 were converted for ICTS. The tanks were first fitted with internal distribution piping and then loaded with ice balls.

By converting the water storage tanks to ice, the system storage capacity increased from 1406.8 kWh to 6893.3 kWh. The use of ICTS in this office building eliminated two installed chillers and reduced maintenance costs by $4000 per year. Other case studies of using ICTS are available in [17], [18] and [19].

6. Sizing chiller and storage capacities for a Kuwait clinic building

In order to size the chiller and storage capacities, a detailed analysis of the combined performance of the chiller and ice storage for each hour of the design day cooling cycle must be performed. However, an initial estimate can be performed by applying simple available formulas and by making some assumptions of the chiller capacity during the day and night time. The basic steps in sizing a cool storage system are as follows [20],

1. Determine accurate building load profile.
2. Select the design day system operating strategy.
3. Calculate the initial size and initial storage capacity.
4. Select the appropriate storage technology.

5. Refine and finalise the chiller and storage equipment selection.

The first and important step in the sizing procedure is to determine an accurate design day building load profile, the system load must then be determined by including all the heat gains associated from pumps and air handling units motors, ducts, and the piping network as well as thermal gains to the storage tank.

Based on the requirement that the total integrated system cooling load must be equal to the total integrated chiller capacity, initial estimation of chiller and storage sizes can be obtained, i.e.

$$\text{Total integrated cooling load (kWh)} = \text{Total integrated chiller capacity (kWh)} \qquad (1)$$

The units of the total integrated system cooling load and chiller capacity are both in kWh. Although, at this stage the chiller capacity is unknown, the capacities relative to some standard condition can be identified for each time period. The chiller capacity may actually vary depending on the condenser and evaporator conditions, but these can be reduced to two conditions depending on the operation mode, chiller capacity when charging the storage tank simultaneously and cooling the building at night time, chiller capacity when direct cooling at day or night times.

$$\text{Total integrated chiller capacity (kWh)} = C_{chil} H_{char} CR_{char} + C_{chil} H_{dirt} CR_{dirt} \qquad (2)$$

where

C_{chil} = nominal chiller capacity.

H_{char} = number of charging hours.

CR_{char} = capacity ratio when charging.

H_{dirt} = number of direct cooling hours.

CR_{dirt} = capacity ratio when direct cooling.

When the chiller charges the storage tank, and at the same time it cools the building the capacity ratio CR, will be equal to the capacity ratio CR_{char}, when charging (i.e. $CR = CR_{char}$).

Nominal chiller capacity C_{chil}, can be obtained by combining equations (1) and (2), and solving for C_{chil},

$$C_{chil} = \frac{\text{Total integrated system cooling load (kWh)}}{H_{char}CR_{char} + H_{dirt}CR_{dirt}} \tag{3}$$

The chiller capacity ratio can be expressed for each cooling mode as a percentage of its nominal capacity. Nominal capacity is selected as the capacity for example at rating conditions of Air conditioning Refrigeration Institute (ARI) USA or any other accepted standards given in [22] provided that necessary correction and provisions are made to suit Kuwait climatalogical design conditions.

For Kuwait, the temperature of the chilled water leaving the chiller was selected to be 6.67°C, and the outside summer dry bulb temperature of 47.4°C entering the condenser was selected for air cooled chillers [23].

For initial chiller and storage sizing of ice storage system, the chilled water leaving the chiller during charging mode is usually in the range of -3C to -6C, the capacity ratio CR_{char} at these temperatures is in the range of 0.6 to 0.7 of the nominal chiller capacity. And during direct cooling when the outlet temperature from the chilller is 6.67°C the capacity ratio CR_{dirt}, is 1.0.

The capacity ratios of CR_{char}, and CR_{dirt}, are chosen as 0.65, and 1.0 of the nominal chiller capacity. This means a 1000 kW capacity chiller will provide 650 kW cooling during charging mode, and provides 1000 kW cooling during direct cooling mode.

The required storage capacity in kWh is equal to the chiller capacity at charging hours minus total integrated system cooling load of the building at charging hours only, i.e.

$$\text{Storage capacity (kWh)} = C_{chil} H_{char} CR_{char} - TC_{char} \tag{4}$$

where

TC_{char} = Total integrated system cooling load at charging hours only

If the system load during the charging hours is zero, the chiller will only charge the storage tank, the second term in equation (4) will be equal to zero or,

$$\text{Storage capacity (kWh)} = C_{chil} H_{char} CR_{char} \tag{5}$$

The CSAT clinic building has been selected to study the applications of ICTS assisted AC system for a building in Kuwait. The building is located within a hospital complex and is comprised of two blocks referred to as A and B, connected by a small corridor. Block A is a single story construction located at the rear part of the building. Block B has ground and first floors in addition to a tall reception area with a large glased area including skylight. This building is occupied from 7:00am to 2:00pm for five days a week, and has a total floor area of 3180 m^2.

British Link Kuwait Company the HVAC designer of the clinic building provided details calculations of the system load for the design day of the building [21]. The building cooling load was determined using Design Database software program by HEVACOM UK. Solar and thermal values for windows are calculated using Window4.1 software program developed by Lawrence Berkley Laboratory USA. Details calculations of the overall heat transfer coefficients for walls, ceiling, roof and ground floor, windows, and lighting, people and appliances schedules and the heat gain from duct, piping system, and pumps AHUs motors are given in the report [21]. A plot of hourly system cooling load and dry bulb temperature of the design day is shown in Figure 8.

The peak system load is 595 kW occurs at hour 3:00pm and when the dry bulb temperature is 46.7°C, the total integrated system cooling load is 9135 kWh, and the diversity is 0.667, the diversity is the ratio of the average to the peak system load.

The peak electrical power and energy consumption of an air cooled chiller at three basic operating strategies are studied in this paper, partial storage load levelling, partial storage demand limiting, and full storage with chiller priority, the chiller is located in series and upstream of the ice cool storage, this design provides simplified control and piping, as shown in Figure 9. The peak power reduction and energy consumption of the chillers at atypical design day of these operation strategies are then compared with conventional operating HVAC system (i.e. without cool storage).

Since the electricity cost in Kuwait is not varied during the day, chiller and storage charging and discharging operations hours must be carefully selected for partial demand limiting and full storage operations. The selection of the operations must be made based on not only the system cooling load profile (i.e Figure 8), but also on the profile of electrical power demand of Kuwait (i.e. Figure 7). In order to select a suitable charging and discharging hours to size the chiller and storage tank, Figures 7 and 8 are plotted together as shown in Figure 10.

Although the system cooling load in Figure 10 at the time of 5:00pm is low, storage charging must be avoided at this hour since the electrical power demand of the country is still high as shown in Figure 10. Storage discharging can be accomplished from hours 12:00pm to 4:00pm, because at these hours, the system cooling load and electrical power demand are both high, therefore reducing the electrical load on both building and power stations.

Brief descriptions of the operations of a conventional AC system and different ICTS operation strategies are given in the following sections. Based on recommended charging and discharging hours in case of using ICTS as shown in Figure 10, an initial chiller and storage sizes were made using equations 3 and 4. The chiller and storage capacities are given in Table 2.

Table 2 shows initial chiller and storage sizes using equations 3 and 4. In a conventional AC system, the chiller was sized based on the peak system load which was 959.2 kW, however, in case of incorporating ICTS with the operation of AC system, the chiller and storage sizes were based on the total integrated system load, the number of selected charging and discharging hours, and the discharging capacity ratio in case of demand limiting partial storage operation strategy.

ECAT2 Version 4.12 Carrier chiller selection software was used to the select suitable air cooled screw chillers using nominal chillers capacities given in table 2. The selection of the chillers were based on temperature of 6.67°C for the leaving chilled water for normal mode, and -5°C for ice mode operations, and inlet condenser dry bulb air temperature to a Kuwait outside design condition of 47.4°C. The cooling production and power consumption of the chillers were obtained for different percentage load and dry bulb temperatures.

Figures 11 to 14 show both hourly cooling productions based on initial sizing using equations 4 and 5, chiller performance data obtained from Carrier chiller selection software, and system cooling load of the building for conventional and different ICTS operation strategies.

7. Conventional operation

In a conventional system, the chiller operates 24 hours to provide sufficient cooling to the building as shown in Figure 11. Most of the time the chiller operates at part load, since in this system design the chiller is selected based on the peak cooling load only of 595.2 kW at 3:00pm not on total integrated load as in the case of cool storage design.

8. Partial (load levelling) operation

The operation of partial storage load levelling is illustrated in Figure 12. The chiller operates at full capacity as much as possible, when the chiller capacity is higher than the system load, the excess cooling from the chiller is stored in the ice tank. When the chiller capacity is less than the building load, the additional requirement of cooling provided is from the tank.

The chiller starts to charging the storage at 5:00pm when the chiller cooling production in charging mode is higher than the system cooling load, and ends at 10:30pm, so the chiller took approximately five and half hours to charge the storage tank. However, in the initial chiller sizing, the chiller took approximately eleven hours to charge the storage, starting at 5:30pm and ending at 4:30am. This is because the selected nominal chiller capacity using the selection software for partial storage load levelling was 531 kW which is higher than 491.8 kW as in the initial sizing chiller capacity. Also the capacity ratio of the chiller during the charging mode was 0.72 which is higher than the assumed value of 0.65 for the initial sizing. At 8:45am the system load exceeded the selected chiller capacity, the exceeded system load was met by the ice tank until 3:20pm where the cooling was met by only the chiller.

9. Partial (demand limiting) operation

Figure 13 shows the operation strategy of a partial storage demand limiting with 0.5 capacity ratio. In the initial chiller sizing, the chiller charges the storage for nine hours, starting from 6:00pm until 4:00am, the chiller was operates at a reduced capacity of 50% for four hours from 12:00am until 4:00pm. At other hours the chiller directly cools the building.

Based on the chiller selection program, the chiller capacity was 610 kW, and it takes only eight hours to fully charge the ice tank starting from 6:00pm until 1:00am with an approximate capacity ratio of 0.67, and then directly meets the cooling load until 12:00pm where it starts to operate at 50% of its full load for four hours. Cooling production can be limited from the chiller by resetting fluid temperature, or by unloading the chiller to a given predetermined percentage of the load.

10. Full storage operation

Full storage operating strategy is shown in Figure 14. In initial sizing, the chiller charges the storage tank for nine hours starting from 6:00pm until 4:00am. The chiller is off for 4 hours from 12:00am until 4:00pm. At other hours the chiller directly cools the building.

Using the performance data of the selected chiller from the selection software, the chiller charges the storage tank for approximately seven hours, from 6:00pm until 1:50am and then directly cools the building until 12:00pm, after that the chiller is switched off for four hours, and the building is cooled by storage tank only. The size of the chiller obtained by the software for full load operation was 813 kW, and the capacity ration during the charging period was 0.66. It must be noted that the chiller capacity ratio at charging and direct cooling modes for full and other storage operation storage strategies is not constant, and it depends on the dry bulb temperature. At a lower dry bulb temperature more cooling can be produced from the chiller.

11. Comparison of different operations

A comparison of conventional AC and ICTS systems is given in Table 3. More data was obtained for demand limiting operation strategy including 60% and 70% capacity reduction during the discharging period.

Full storage has the maximum chiller and storage sizes however it has the lowest power at the peak load. The size of the chiller and storage capacities in full load operation increased 33% and chiller energy consumption increased by 8% comparing with the conventional system.

Partial storage load levelling operation has the lowest chiller and storage sizes, and it reduces the peak electrical power by only 19%, consumes 2% more energy, and the chiller size is reduced by 13% compared to conventional AC system.

The chiller and storage sizes in partial storage demand limiting operation with 50% capacity ratios is larger than the partial storage load levelling and lower than full storage operations, and has same energy consumption to full storage. The energy consumption is 8% higher and the electrical power at peak load is 50% lower compared to conventional AC system.

Table 3 also shows that the percentage reduction in the peak power of demand limiting operation compared to conventional operation with 50%, 60%, and 70% capacity at discharging hours is 50%, 45%, and 35% respectively. Also, for demand limiting partial storage, the energy consumption of the chiller, and chiller and storage sizes decreases with the increase in the chiller capacity during the discharging hours.

Further analysis has conducted based on the selection of the charging hours in an attempt to reduce the energy consumption of the chiller using different ICTS operation strategies. For example, the results obtained in Table 3 for ICTS for demand limiting partial and full storage operations were based on the selected charging hour starting at 6:00pm. The energy consumption of the chiller could be reduced by shifting the charging time by two or three hours later to take advantage of lower dry bulb temperature and system cooling load.

For partial load levelling, the charging time was shifted from 5:00pm to 9:00pm, reducing the percentage increase in the chiller energy consumption from 2% to 0%. For partial with 50%, and 70% demand limiting, and full storage operations, by changing the charging time from 6:00pm to 8:00pm, the percentage of the energy consumption reduces by 2%, 2%, and 3% respectively. Finally, changing the charging time from 6:00pm to 9:00pm of partial with 60% demand liming operation reduces the energy consumption by 2%.

Hourly power demand of the conventional and ICTS operations is shown in Figure 15. Full storage and partial load levelling operations reduce the electrical power during the peak load hour (at 3:00pm) by 321kW and 62kW respectively compared to conventional AC operation. And the reduction in the peak power of demand limiting partial storage operation with 50% capacity compared to conventional operation was 161kW.

The maximum chiller power withdrawn from the utility for full and partial storage 50%, 60%, and 70% demand limiting operations were 414kW, 317kW, 317kW, and 278kW at 6:00pm respectively. For conventional and partial load levelling operations the maximum power withdrawn were 321kW and 260kW at 3:00pm respectively.

12. Conclusion

It has been found that incorporating ICTS with a conventional AC system can reduce the peak electrical demand during the peak electrical load period and increase chiller energy consumption of the AC system. The amount of reduction in electrical power depends on the operation strategy that is selected for ICTS. Full storage has the highest electrical reduction, however, chiller and storage sizes are high compared with other operation strategies. Full as well as partial load levelling and demand limiting operations consume more energy than a conventional AC system. It has been also found that the amount of energy consumption can be reduced by shifting the charging time from 6:00pm to 8:00pm and 9:00pm to take the advantage of lower dry bulb and system cooling load.

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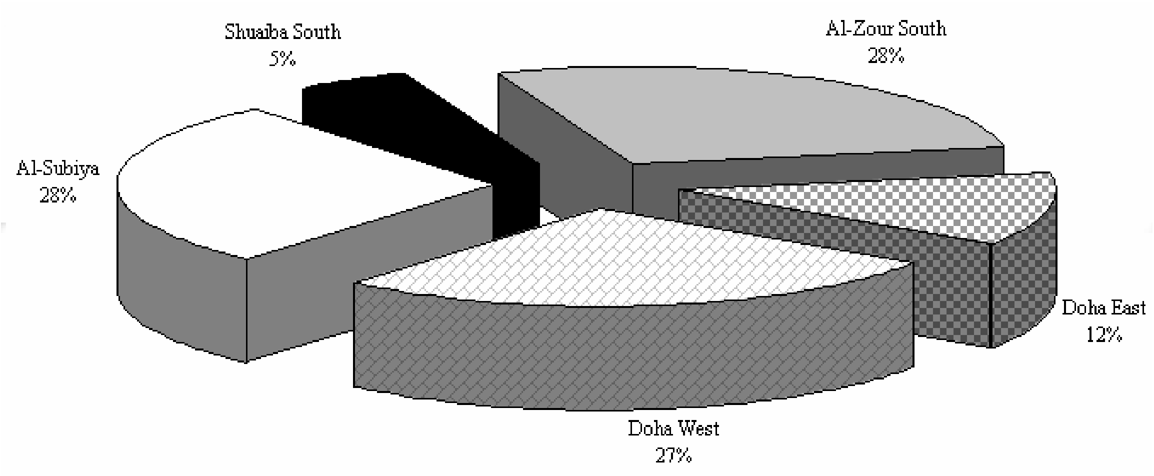


Fig. 1. Percentage distribution of peak electrical load generation by different power stations in Kuwait [1].

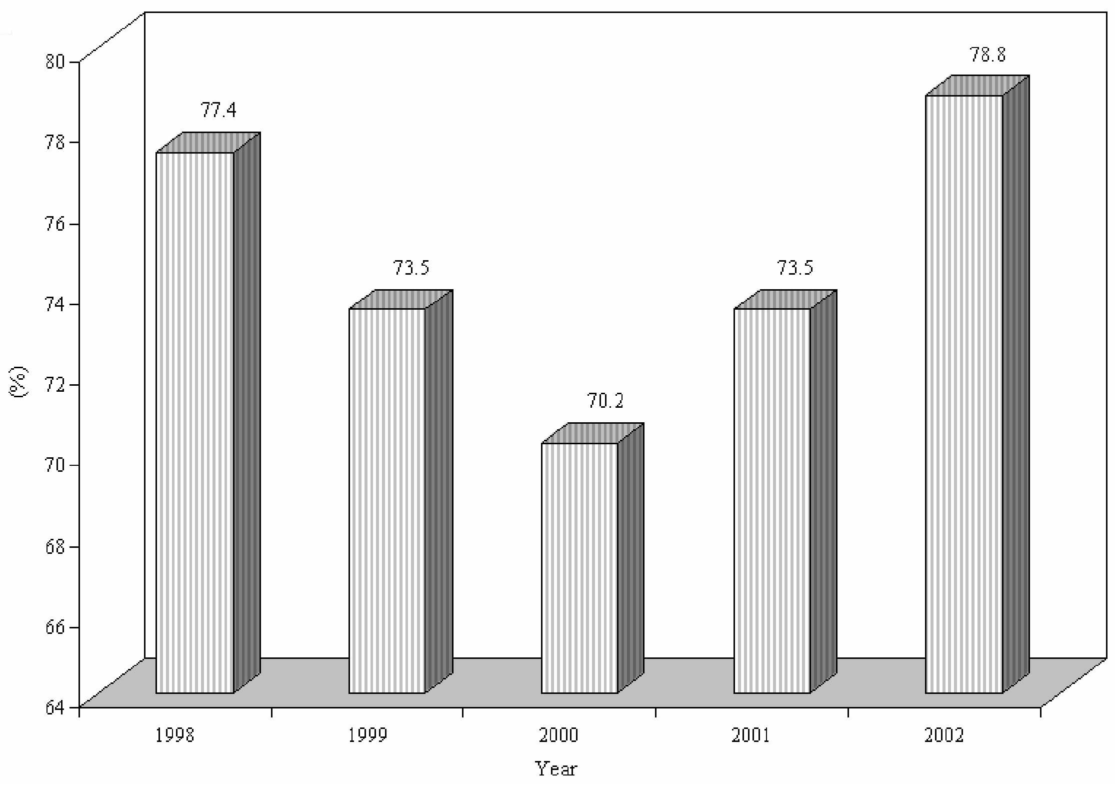


Fig. 2. Peak load as a percentage of installed capacity for year 1998-2002.

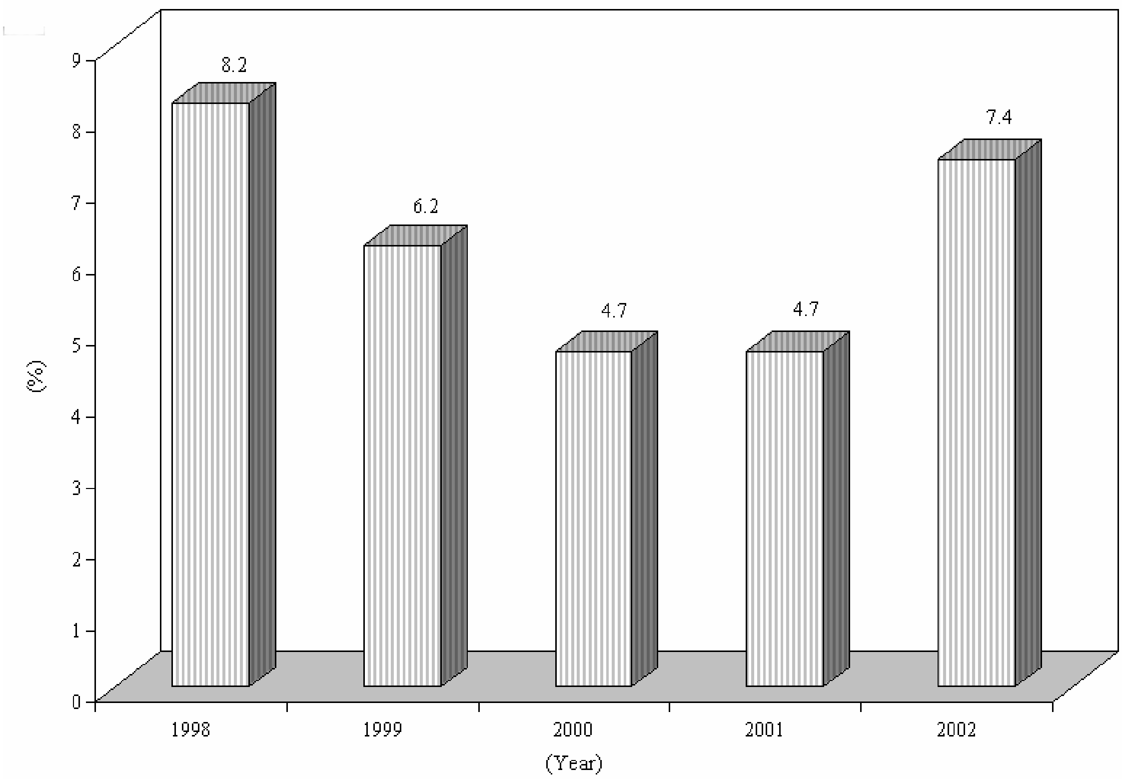


Fig. 3. Percentage increase in annual peak electricity load for year 1998-2002.

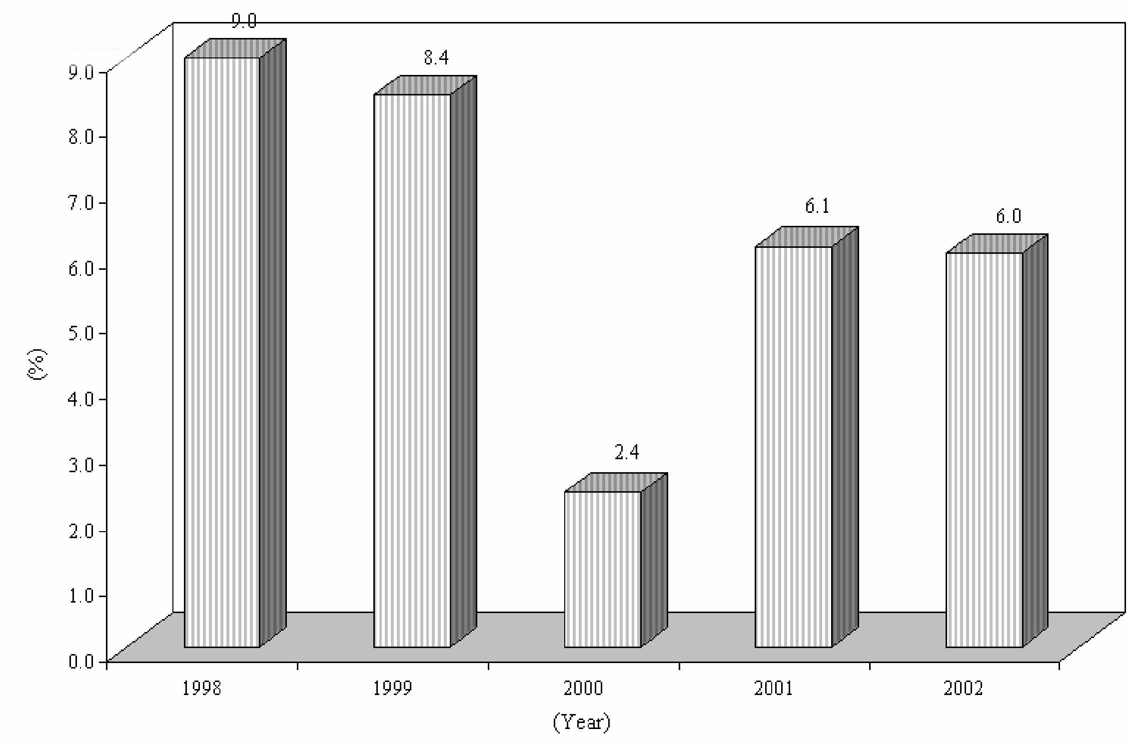


Fig. 4. Percentage increase in annual electrical energy for year 1998-2002.

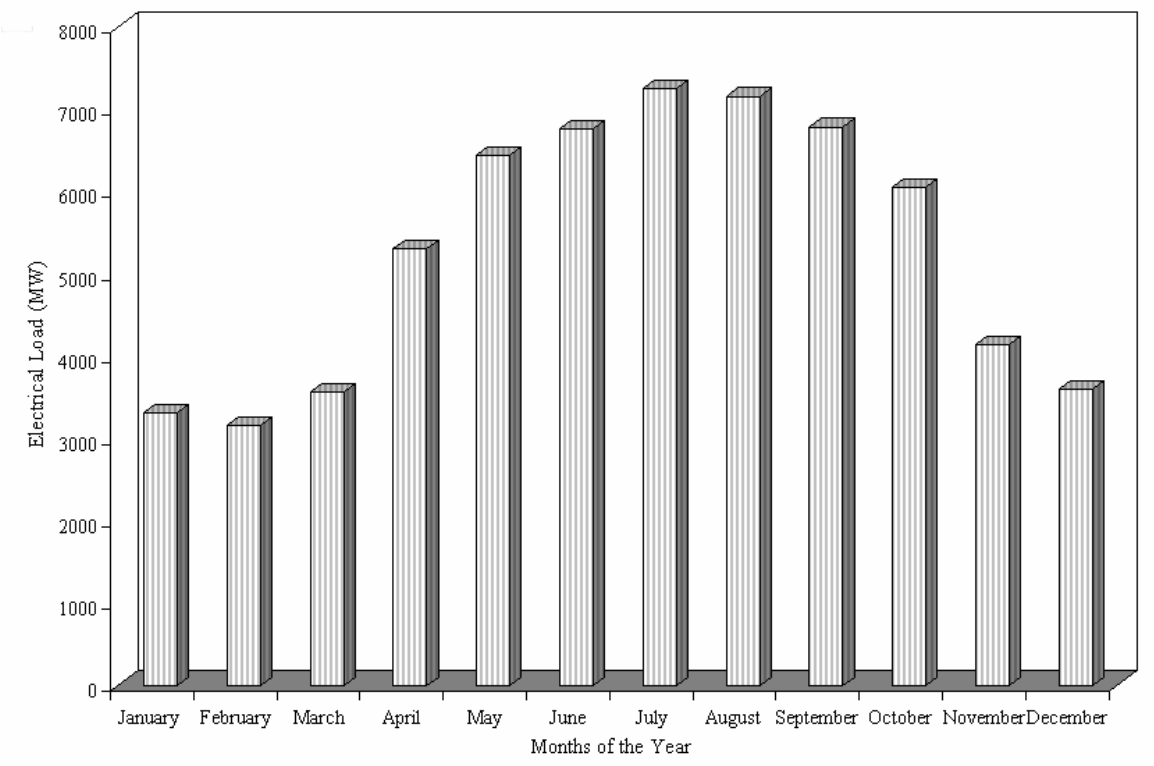


Fig. 5. Monthly maximum electrical load for year 2002.

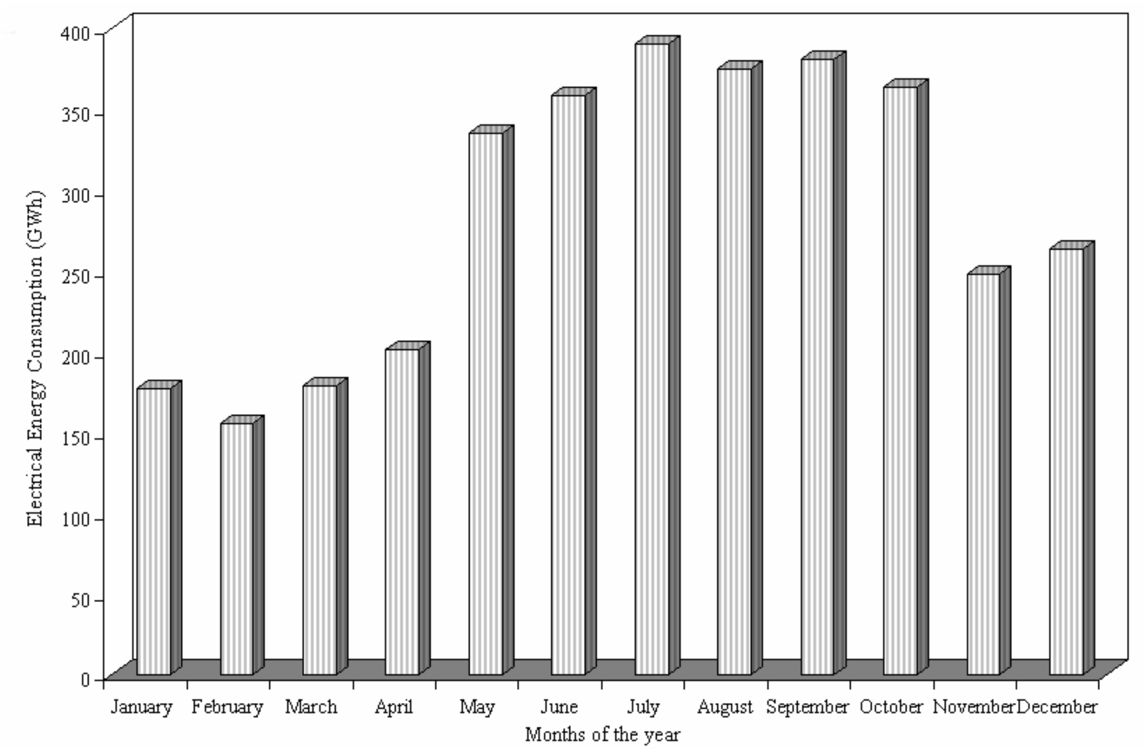


Fig. 6. Monthly electrical energy consumption for year 2002.

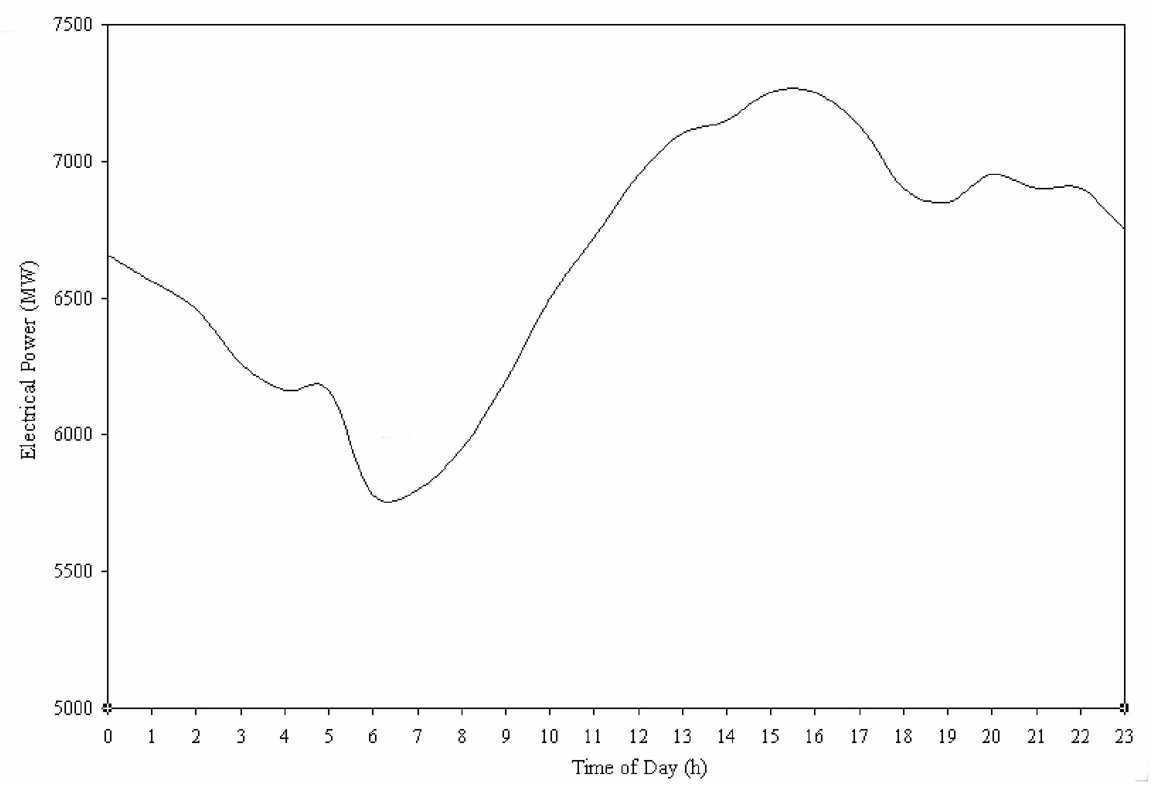


Fig. 7. Peak day hourly electrical power consumption for year 2002.

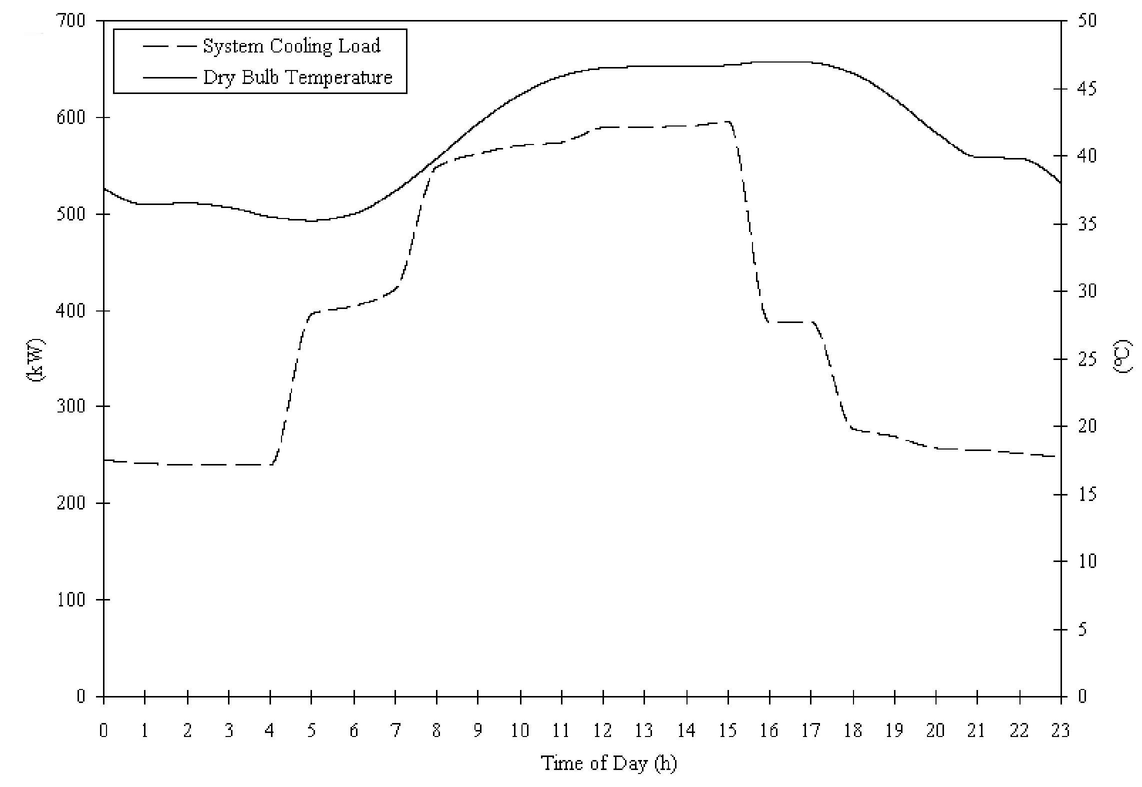


Fig. 8. Profiles of hourly system cooling load and dry bulb temperature.

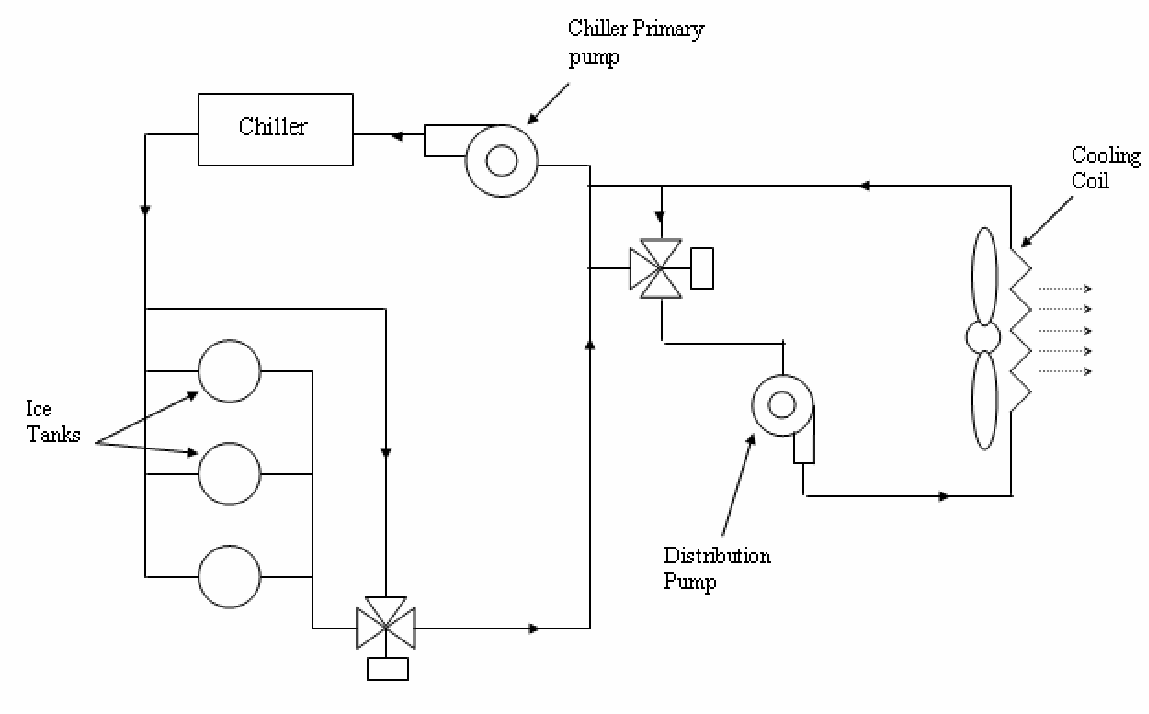


Fig. 9. Series Flow – Chiller Upstream with primary/Secondary pumping Circuits.

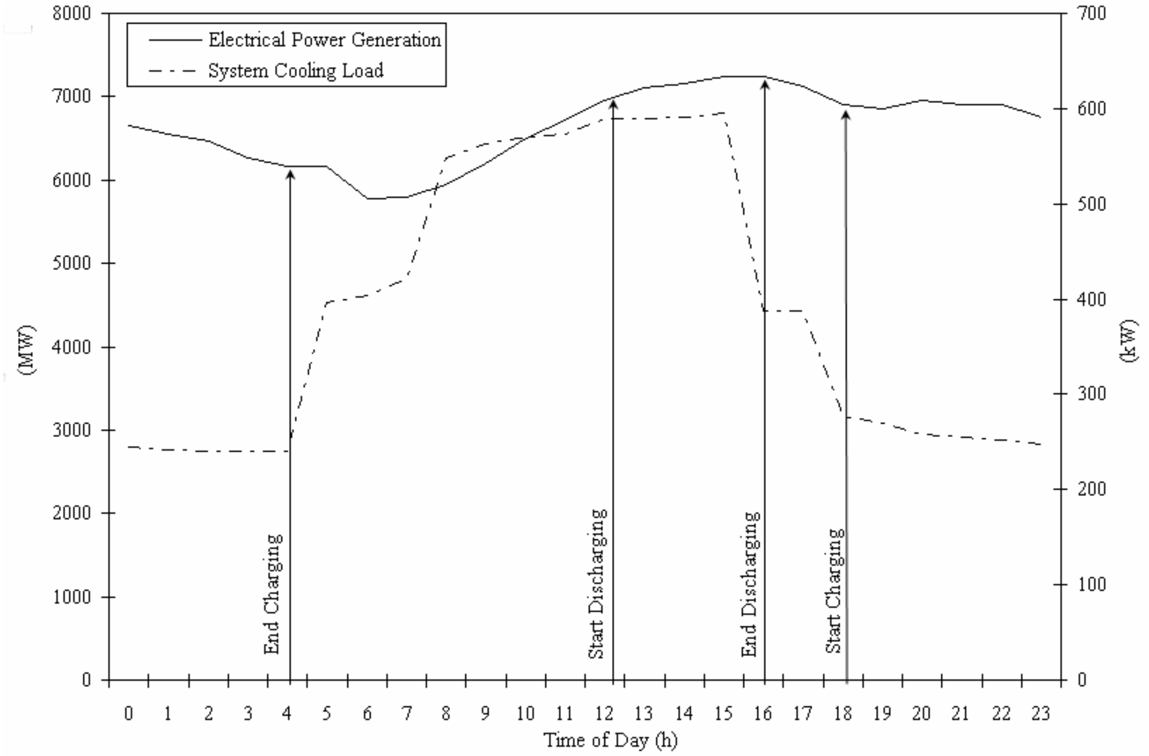


Fig. 10. Selecting charging and discharging time.

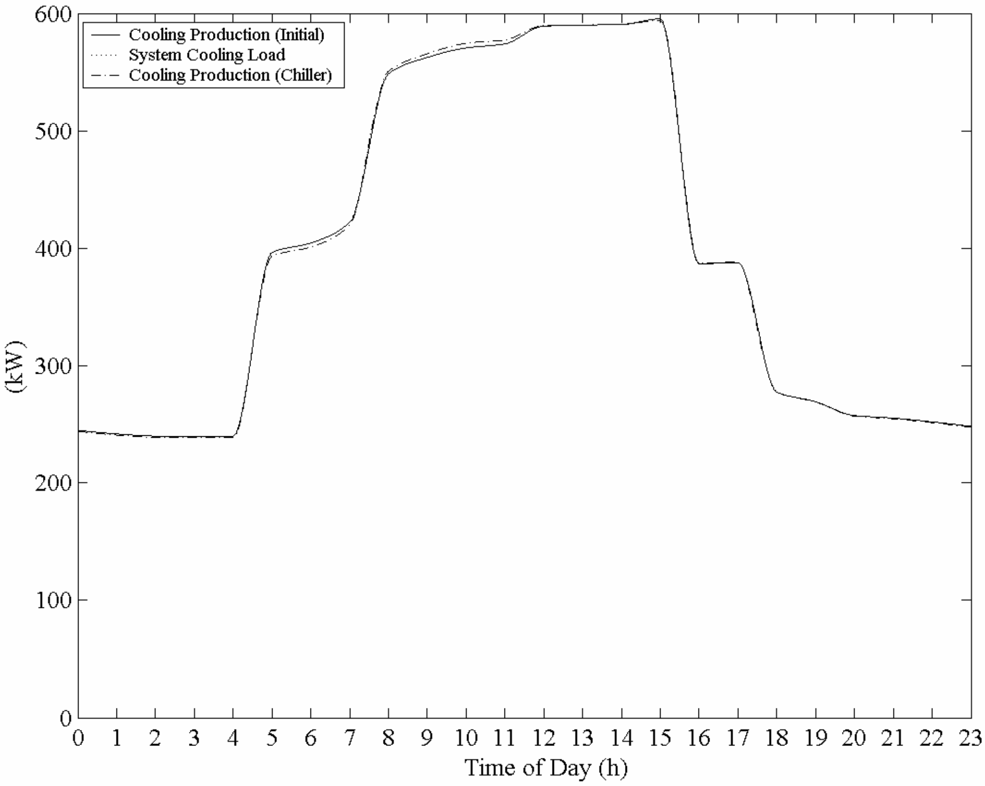


Fig. 11. Conventional operation.

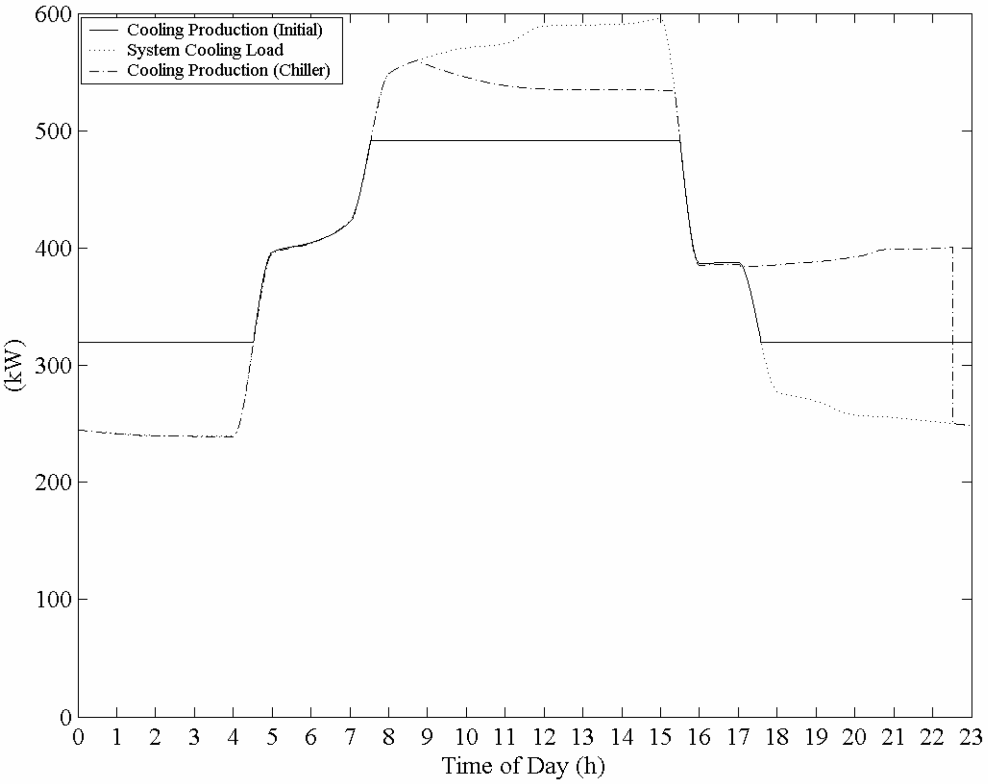


Fig. 12. Partial (load levelling) operation.

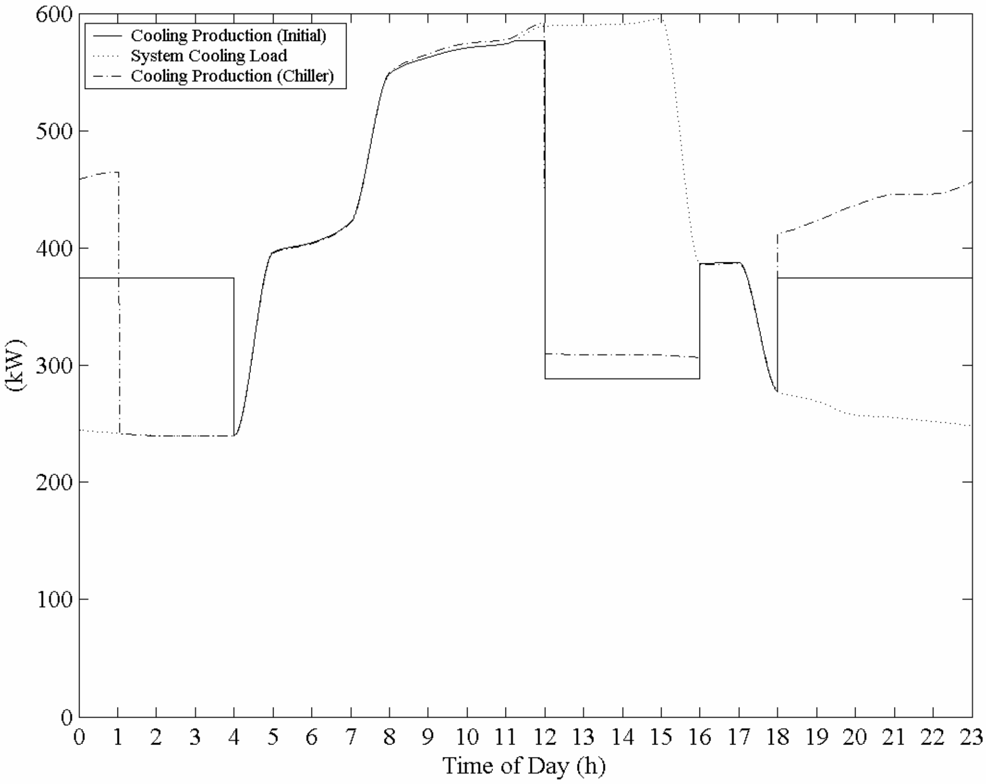


Fig. 13. Partial (demand limiting) operation.

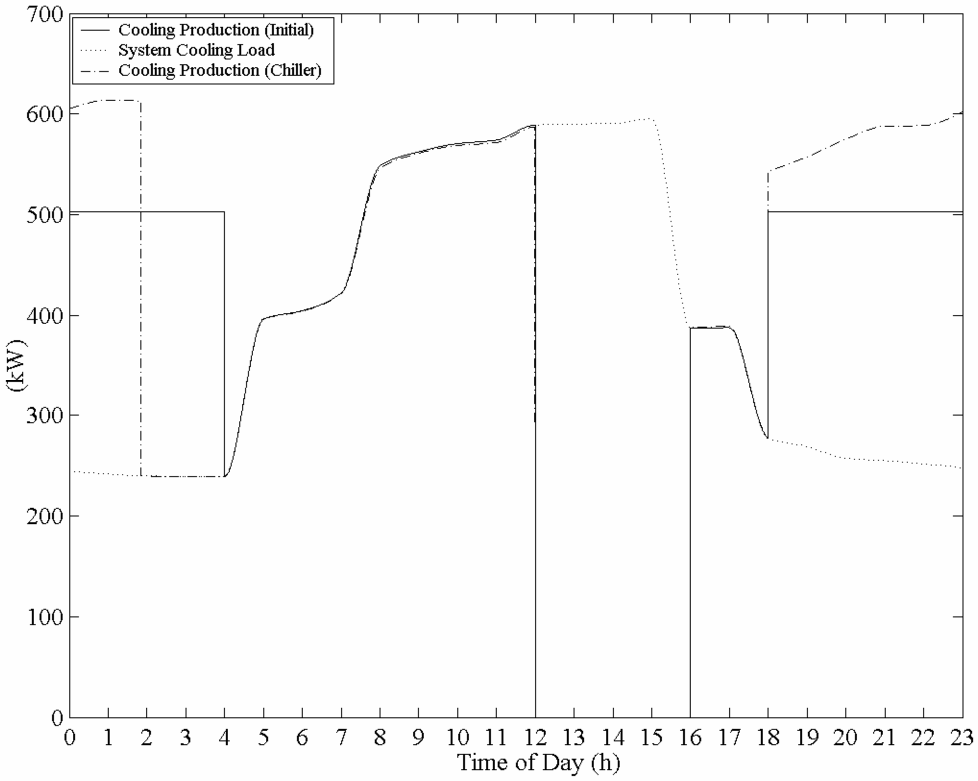


Fig. 14. Full operation.

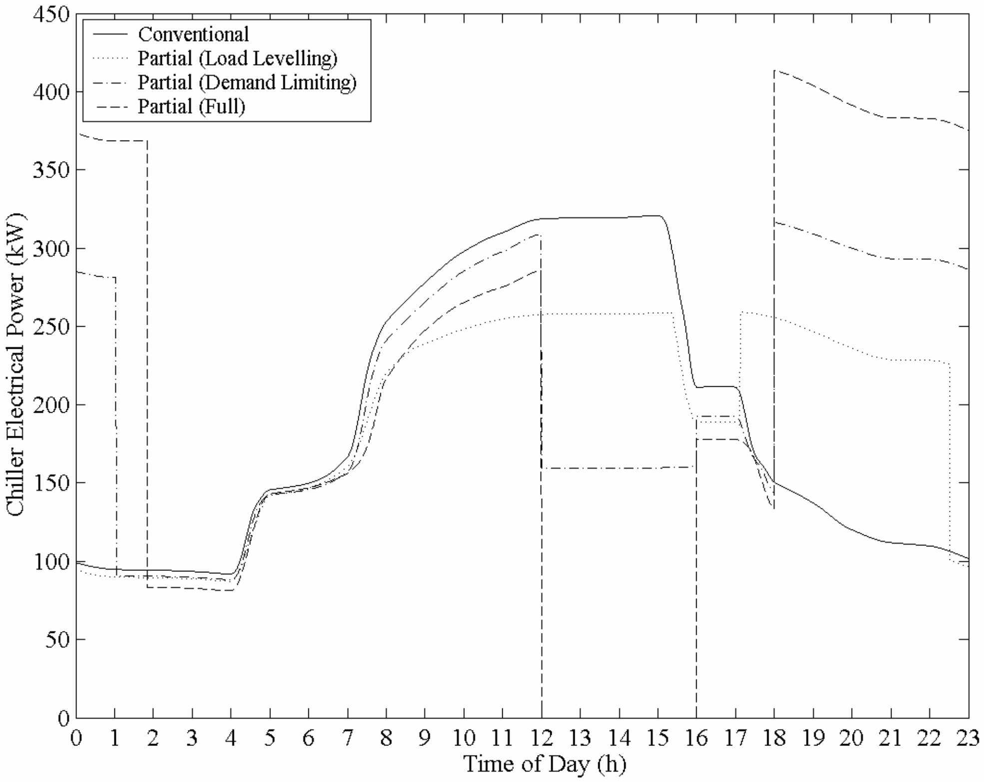
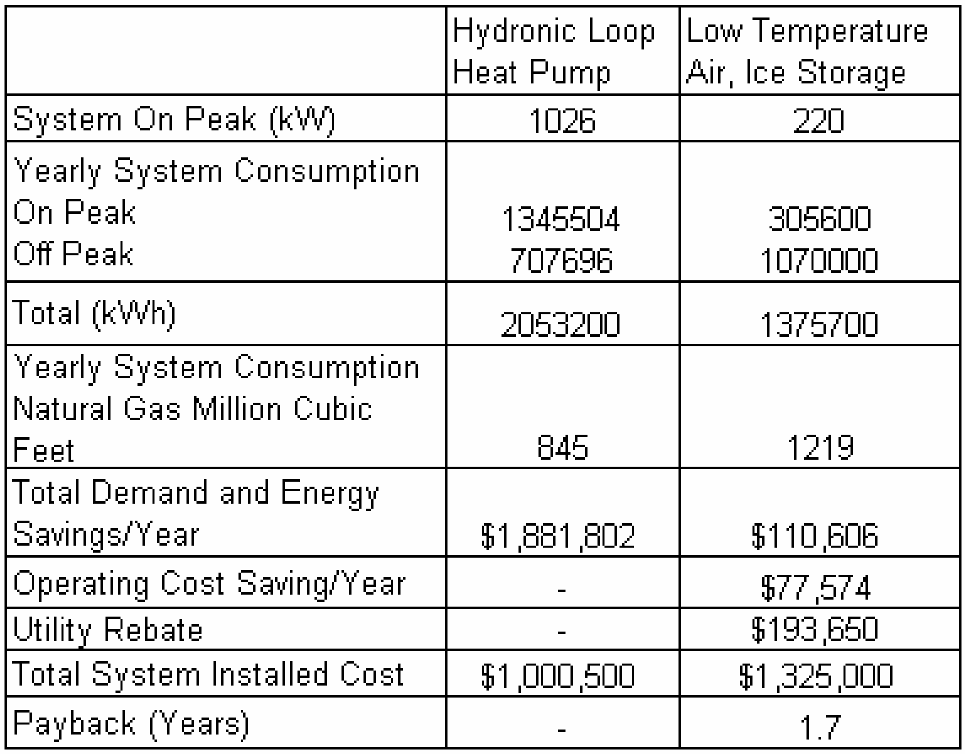


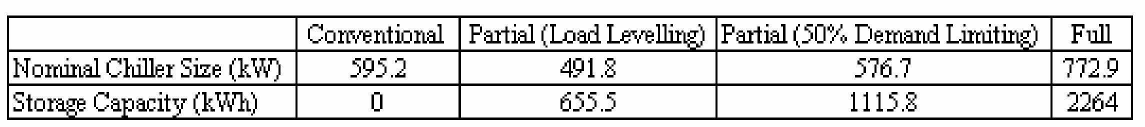
Fig. 15. Hourly power demand of various AC operation.

Table 1. Analysis of demand and energy payback [7].



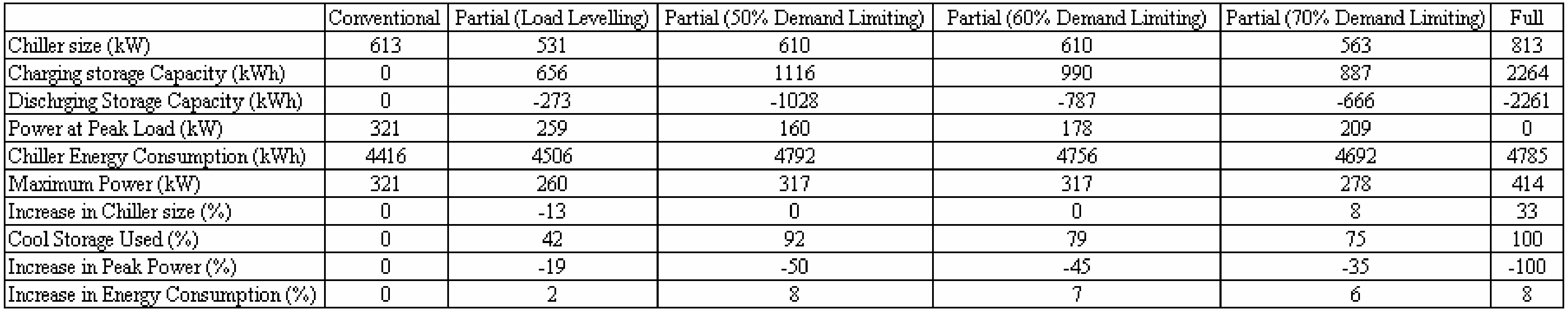
	Hydronic Loop Heat Pump	Low Temperature Air, Ice Storage
System On Peak (kW)	1026	220
Yearly System Consumption On Peak Off Peak	1345504 707696	305600 1070000
Total (kWh)	2053200	1375700
Yearly System Consumption Natural Gas Million Cubic Feet	845	1219
Total Demand and Energy Savings/Year	$1,881,802	$110,606
Operating Cost Saving/Year	-	$77,574
Utility Rebate	-	$193,650
Total System Installed Cost	$1,000,500	$1,325,000
Payback (Years)	-	1.7

Table 2. Initial chiller and storage capacity sizes.



	Conventional	Partial (Load Levelling)	Partial (50% Demand Limiting)	Full
Nominal Chiller Size (kW)	595.2	491.8	576.7	772.9
Storage Capacity (kWh)	0	655.5	1115.8	2264

Table 3. Comparison of conventional and ICTS operation strategies.



	Conventional	Partial (Load Levelling)	Partial (50% Demand Limiting)	Partial (60% Demand Limiting)	Partial (70% Demand Limiting)	Full
Chiller size (kW)	613	531	610	610	563	813
Charging storage Capacity (kWh)	0	656	1116	990	887	2264
Dischrging Storage Capacity (kWh)	0	-273	-1028	-787	-666	-2261
Power at Peak Load (kW)	321	259	160	178	209	0
Chiller Energy Consumption (kWh)	4416	4506	4792	4756	4692	4785
Maximum Power (kW)	321	260	317	317	278	414
Increase in Chiller size (%)	0	-13	0	0	8	33
Cool Storage Used (%)	0	42	92	79	75	100
Increase in Peak Power (%)	0	-19	-50	-45	-35	-100
Increase in Energy Consumption (%)	0	2	8	7	6	8