

The impact of using chilled water storage systems on the performance of air cooled chillers in Kuwait

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Abstract

In the Air Conditioning (AC) industry Chilled Water Storage (CWS) systems are one form of cool thermal storage technology that can be used to time shift the electrical load of the system from the peak day periods to off peak night time periods. In this paper the data for the actual exported and generated electrical energy obtained for the power stations in Kuwait has been used to estimate the electrical energy consumption and the peak electrical load of AC systems. Since the chiller in an air cooled AC system represent more than 75% of the total electrical power consumed by an AC system during the peak demand period, the impact of using CWS systems with alternative operating strategies including partial (load levelling), partial (demand limiting), and full load has been investigated. In our conclusions we estimate that approximately 45% of the total annual exported electrical energy is consumed solely by AC systems as a result of the very high ambient temperatures occurring between March and October. Furthermore, it is estimated AC systems represent about 62% of

the peak electrical load. The results demonstrate that CWS can reduce the peak electrical load of a chiller in an air cooled AC system by up to 100% and reduce the nominal chiller size by up to 33% depending upon the operating strategy adopted. This is achieved with only a 4% increase in power consumption of the chiller for all CWS strategies except for full storage where the energy consumption actually decreases by approximately 4%.

Keywords: chilled water storage; peak power; energy consumption; Kuwait; air cooled; coefficient of performance; air conditioning; energy consumption

1. Introduction

The demand for electricity in Kuwait is continuously increasing, growing at an average rate of 6.2% per year [1] well above the world average of 2.7% [2]. As a consequence, in order to maintain a 20% reserve capacity, additional power plants must be constructed to satisfy this demand. It was reported in [3] that Kuwait must invest around US\$ 4 billion over the next ten years to finance an expansion programme for an additional 3,400 megawatt electricity (MW_e) to cope with this predicted demand.

Kuwait is one of many countries in the world with a hot dry climate that relies heavily upon AC systems for the cooling of buildings. AC systems have become a necessity for the modern life style to provide adequate comfort and a healthy indoor climate. As will be shown later, AC systems of buildings in Kuwait consume about 62% of the peak electrical power and 45% of the annual exported electricity. Based on the analysis of the statistical electricity data provided by the Ministry of Energy of Kuwait for years the 1998 to 2003, Sebzali and Rubini [1] estimated that the average

increase in annual peak electrical demand was 6.2% and electrical energy consumption was 6.4% and that in 1998 the percentage growth of maximum electricity demand and electrical energy consumption reached a maximum value of about 8% and 9% respectively.

Cool thermal storage has many benefits which are discussed and reported in [4] including the economics, energy saving, design consideration and impact on the environment. The feasibility of incorporating cool thermal storage into conventional AC systems was studied in [5] and [6] where cool thermal storage was considered as one of the available energy saving technologies.

Chilled Water Storage (CWS) [7] is one cool thermal storage technology that is widely used in many countries including the UK and USA to shift the peak electrical power requirements from periods of high demand, to periods of lower demand. Many CWS systems have been installed in the USA. For example in 1996 a 8517 m³ storage tank was installed for an Army installation to shift more than 3 MW_e of electrical demand from day to night time periods [8]. The electrical cost savings for this installation were reported to be about US\$ 430,000 [8]. Based on a survey of cool thermal storage reported in [9], CWS systems account for 10% of the total cool thermal energy storage capacity installed in the USA, with an average system capacity of 50,300 kilowatt cooling (kW_ch) and an average storage tank volume of 4804 m³. Also [9] showed that CWS systems dominate for large buildings greater than 87,900 kW_ch of stored cooling.

In the Gulf area some of the buildings in Saudi Arabia have integrated cool thermal storage in their cooling systems. A list of major projects using both chilled and ice thermal storage systems is reported in [10]. A preliminary study reported in [11]

shows that thermal energy storage can reduce the peak cooling load demand by approximately 30 to 40 % and the peak electrical demand by approximately 10 to 20%. Further discussion, application, and economic analysis of thermal energy storage in Saudi Arabia is reported in [12].

For Kuwait, Sebzali and Rubini [1] studied the impact of using ice thermal storage, with different operating strategies, on the energy performance of air cooled chillers. Although [1] found that ice thermal storage can reduce the electrical load during the peak periods of cooling demand, the energy consumption increased by up to 8%, depending on the operating strategy, compared to a conventional AC system. The increased energy consumption of the chillers will additionally increase the operating cost of these types of system, because the cost of the electricity is directly proportional to the energy consumption by the cooling system, which in Kuwait does not vary between day and night time.

2. Objectives

This paper extends the work reported in [1] by further studying the impact of a CWS system on the energy performance of air cooled chillers for the Kuwaiti climate. Different operating strategies are considered in order to determine the optimal strategy by which the peak power of a cooling system can be reduced during the maximum cooling demand period, whilst at the same time reducing overall energy consumption.

The chiller in an air cooled AC system consumes the greatest power at the peak load, representing about 78% of the peak power consumed by the AC system. Therefore, the impact of incorporating CWS on the power and energy consumption and Coefficient Of Performance (COP) of air cooled chillers is specifically examined.

This is achieved by employing available test performance data for an existing air cooled screw chiller model.

With a CWS system different operating strategies for the AC system can be implemented, including load levelling, demand limiting partial storage and full storage strategies. The effect of these operation strategies on chiller and storage sizes, peak power, energy consumption and COP for an air cooled chiller is studied.

For Kuwaiti conditions, the use of a CWS system in a conventional air cooled AC system may have a greater advantage over water cooled AC systems. This is because of the larger variation that occurs in the dry bulb temperature compared to the wet bulb temperature during a 24 hour period. Air cooled chillers can operate more efficiently by taking the advantage of the lower dry bulb temperature during the night to more efficiently charge the storage tank.

In Kuwait, there is no cheap rate electricity tariff and there is no direct cash incentive offered by the Ministry of Energy for demand management measures. However, CWS systems may be attractive for both the costumer and the Ministry if:

1. The electrical power consumption during the maximum cooling demand is reduced.
2. Chiller operation during the night time improves energy conservation and hence operating cost.
3. Cooling system and power connection costs are reduced.

3. Estimation of the electricity consumption of air conditioning systems

A reasonable estimate can be obtained for the annual electricity generation in gigawatt electricity (GW_e h), and the maximum power demand in MW_e at the peak time in the day by using the statistical published electricity data [13-15] and actual measurements of the hourly electricity generation throughout the year provided by the control department in the Ministry of Energy.

To estimate the annual electrical energy required for the operation of AC systems, the monthly exported electrical energy data from power stations in Kuwait for the years 2001 and 2003 [13-15] was analysed.

Using the exported electrical energy data, an estimate of the electrical energy required by AC systems was obtained based on the assumption that the exported electrical energy in the month of February is neither used for heating nor for cooling. This was based on the observation that the month of February has the lowest electrical energy compared to other months in the year. This is constant throughout the year and represents about 53% of the total exported electricity. This would appear to be a significant proportion, but in fact is a reasonable estimation because this represents not only the power consumption from different appliances in buildings and street lighting, but also the operation of major industries such as factories, refineries, and large petrochemical companies.

Taking the difference between exported electrical energy in February from other months and assuming that energy in January and December is utilised for heating only, then the summation of the load from March to November may be assumed to represent the energy use by AC systems in buildings. Applying this simple calculation

to the data for the years 2001, 2002, and 2003, the electrical energy consumption by AC systems was determined to be 13,000, 14,150, and 15,000 GW_eh respectively, increasing by 14% in only two years. The average annual percentage of the electrical energy consumed by AC systems over three years, is 45% of the total exported and 39% of the total generated energy from all power stations in Kuwait. The proportion of the electrical energy for the operation of AC systems in the year 2003 was determined to be 46% of the exported and 39% of the energy generated

The hourly electrical load for every power station in Kuwait was obtained for the year 2003 to provide an estimate of the electrical load of the cooling systems in Kuwait. The difference in the electricity demand between August and February at the peak time of 2:00 pm, implies that the power requirement of AC systems is about 4,400 MW_e . This represents about 62% of the average peak load in August. The demand for electricity in February at 2:00 pm represents the power consumed by different appliances, auxiliary units within the power stations and production of distilled water, which is estimated to be about 2,650 MW_e .

4. Recommended power rating of the air conditioning system in Kuwait

The recommended power rating in kilowatt electricity per kilowatt cooling (kW_e/kW_c) for air cooled and water cooled AC systems at the design conditions for Kuwait was reported [16]. This was generated based on a market survey of the latest AC equipment manufactured or marketed in Kuwait and an experimental investigation conducted on a number of systems of different capacities and type and the realities of weather conditions.

In air cooled systems the main components that consume electricity are the chiller (e.g. cooling production) compressor, condenser fans, air handling units (e.g. air distribution) and chilled water pump (e.g. water distribution) motors. The recommended total power rating for an air cooled chiller system is $2.05 \text{ kW}_e/\text{kW}_c$ [16]. The chiller, air handling unit and pump motors represent about 78%, 18.5%, and 3.4% of the total power rating respectively at the peak cooling demand.

In water cooled systems the main components that consume electricity are similar to that of the air cooled systems but with the addition of the condenser water pumps and cooling tower fans motors. For larger water cooled systems the power requirements of the chiller at peak load is lower and for other components is higher. The share of the power demand of the air handling units ranges between 25 to 30% which is greater than air cooled systems. Furthermore, the average power rating of water cooled systems is approximately 34% less than the air cooled systems [16].

Based on the study conducted in [16], the peak power requirements and seasonal energy requirements of water cooled systems are less than air cooled systems by 17 to 47% and 23 to 44% respectively depending on the location, type, and building cooling load. Although water cooled systems have a lower peak power requirement and lower energy consumption they have higher life-cycle costs compared to air cooled systems because of high maintenance costs and the added cost of desalinated water [16]. It is for this reason that the use of cool thermal storage with air cooled systems is more attractive than with water cooled systems, since this will further reduce the peak power demand, of which, approximately 78% of the total power of the cooling system is due to the chiller.

5. Determination of chiller, storage capacities and storage volume

5.1. The building cooling load

A clinic building in Kuwait was selected to study the impact of using a CWS system on the electrical power and energy consumption of the chillers. The building is located within a hospital complex comprising 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 glassed area including skylight. This building is occupied from 7:00 am to 2:00 pm for five days a week, and has a total floor area of 3180 m².

The HVAC designer of the clinic building, British Link Kuwait Company, provided detailed calculations of the system load (e.g. building plus heat gain by the auxiliary systems) for the design day of the building [17]. Detailed calculations of the overall heat transfer coefficients for the building, the schedules of lighting, people, appliances and the heat gain from ducts, piping systems and pumps and air handling unit motors were all reported [17]. The peak system load is about 595 kW_c occurring at 3:00 pm when the dry bulb temperature is about 47°C. The total integrated system cooling load is 9,100 kW_ch, and the diversity is 0.67. The diversity is defined as the ratio of the average to the peak system load.

5.2. Operating strategies of chilled water storage systems

The operating strategy of a CWS system has a significant effect on the size of the chiller and the storage capacity and hence on their capital costs. Furthermore, the reduction of peak electrical power and electrical energy consumption of the chillers is strongly dependent on the operating strategy of the system. In this paper, different

operating strategies are examined and compared to a conventional AC system. The operating strategies include, partial storage load levelling, partial storage with 50, 60 and 70% demand limiting and full storage.

5.3. Selecting suitable charging and discharging time

Since the cost of electricity in Kuwait does not vary during a 24 hour period, the time at which the CWS is charged and discharged must be carefully selected if the system is to be designed for partial demand limiting and full storage operating strategies. The selection of the charging and discharging time must be considered based on the profiles of both the system cooling of the building and the electricity power generation of Kuwait. The profiles of the system cooling load of the clinic and the electricity power generation for Kuwait [13] are shown in Fig. 1.

Although the system cooling load at 5:00 pm is low, the charging of the CWS must be avoided at this time since the demand for electricity is still high as shown in Fig. 1. Storage discharging should occur from 12:00 pm to 4:00 pm because during this time the system cooling load and electricity demand are both high, therefore reducing the electrical load on both the building and power stations. Generally the choice of charging and discharging time depends upon a given building load profile. If a building has a different load profile than the one shown in Fig. 1, then the charging and discharging times will change accordingly.

5.4. Final sizing of the chiller and the storage capacities

Using the system cooling load profile of the clinic building as shown in Fig. 1 and applying the recommended charging and discharging times as discussed above, the

sizes of the chiller and the storage capacities were obtained for the different operating strategies by applying Eq. (1) and (2) [18] e.g.

$$C_{\text{chil}} = \frac{\text{Total integrated system cooling load(kW.h)}}{H_{\text{char}} \text{CR}_{\text{char}} + H_{\text{dirt}} \text{CR}_{\text{dirt}}} \quad (1)$$

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.

and

$$\text{Storage capacity} = C_{\text{chil}} H_{\text{char}} \text{CR}_{\text{char}} - \text{TC}_{\text{char}} \quad (2)$$

Where

TC_{char} = Total integrated system cooling load during charging time only.

In Eq. (1), 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 [19], provided that necessary correction and provisions are made to suit the Kuwait.

In a CWS system, the typical chilled water temperature exiting the chiller during the period of charging, discharging and direct cooling is usually in the range of 4 °C to 5.5 °C [18]. Therefore, for sizing of the chiller and storage capacities, the capacity ratios of the chiller were assumed equal to 1 (i.e. similar to a conventional AC system) during charging, CR_{char} , discharging, and direct cooling CR_{dirt} .

The chiller capacity obtained from Eq. (1), was then substituted into Eq. (2) to determine the required storage capacity in kW_{ch} , for each operating strategy. This is equal to the difference between the nominal chiller capacity during the charging period and the total integrated system cooling load of the system during the charging period only.

The storage capacity obtained from Eq. (2) was used to determine the volume of the tank [18] e.g.

$$V = \frac{3600 \times \text{Storage capacity}}{\rho c_p (T_i - T_o) (\text{figure of merit})} \quad (3)$$

where

V = Volume of the tank in m^3 .

ρ = Water density in kg/m^3 .

T_i = Inlet chilled water temperature to the storage tank during discharging in °C.

T_o = Outlet chilled water temperature from the storage tank during discharging °C.

For most storage tanks the temperature of the discharge ranges between 4.4 °C to 7.0 °C, and the return from 10 to 18 °C. Storage tanks with a good design of diffuser can

perform at a figure of merit of 90% or better [18]. The figure of merit can only be accurately estimated from field data or from scale model testing of similar geometries. In the absence of such data, a factor of 0.85 to 0.90 was used as proposed by Dorgan [18].

Eq. (3) was applied to determine the volume of the storage tank for different operating strategies based on a figure of merit of 0.9, an average discharge temperature of 5.4 °C, and return water temperature of 15.6 °C. The results of sizing the chiller, storage capacities and tank volumes for different operating strategies are summarised in Table 1.

6. Chiller cooling production, power and COP profiles for different operating strategies

ECAT2 Version 4.12 Carrier [20] chiller selection software was used to select suitable air cooled screw chillers using the nominal chiller capacities previously given in Table 1 and based on recommended guidelines given in [19] and [21]. ECAT2 provides performance data based upon a factory run test for each model of chiller at the full load design point and at the part load operating points as required.

The performance data of the selected chiller at part load operating points was obtained, including percentage load, gross capacity, absorbed power and COP. This was performed by manually entering the percentage unloading steps and the dry bulb temperatures of the condenser inlet air. In order to obtain a proper step in the percentage of the gross capacity (e.g. 5% step in gross capacity and 3 °C step in dry bulb temperature were used in this paper), the input of the unloading steps was adjusted accordingly. The cooling production and power consumption required by

each chiller for the clinic building were determined by simple two dimensional interpolation of the data.

In the case of chillers running with CWS, it was assumed that the chillers were operating at full capacity during the charging period (e.g. 100% capacity) and during the discharge period were either switched off, operating at full load, or operating at a given percentage capacity (e.g. 50% demand limiting) depending on the operating strategy. During the charging period, it was assumed that the chillers match the system load, at the same time storing cold water in the storage tank. When the tank is fully charged, it was assumed that the chillers directly match the building load. The results of the cooling production, power consumption, and the COP are analysed in the following subsections.

6.1. Cooling production profile

Fig. 2 illustrates the hourly cooling production profile for the conventional chiller and for chillers operating with CWS for different operating strategies, load levelling, demand limiting partial storage and full storage. In the conventional system, the chiller operates continuously throughout a 24 hour period to provide sufficient cooling to the building as shown in the figure. From Fig. 2, it can also be observed that the profile of the cooling production is similar to the system load profile shown in Fig. 1. In this configuration, the chiller runs for most of the time at part load and at full or nearly full load for only a few hours during the peak cooling demand period.

In the partial storage, load levelling operating mode, the chiller operates at full load capacity for the maximum possible time as shown in Fig. 2. When the chiller capacity is higher than the system load, the excess cooling from the chiller is stored in the

storage tank (e.g. charging mode). When the chiller capacity is less than the system load, the additional requirement of cooling provided is taken from the tank (e.g. discharging mode). The chiller starts to charge the storage at about 4:00 pm when the capacity of the chiller is higher than the system cooling load and ends at about 3:00 am when the tank is fully charged, so the chiller takes approximately 12 hours running at full load to fully charge the storage tank. Fig. 2 also shows that when the chiller operates at full load during the night time period more cooling is produced, this is because of the lower dry bulb temperatures at night. This system design is effective where the peak cooling load is much higher than the average load and also the lowest initial cost compared to conventional and other storage strategies [4].

In a 50% demand limiting partial storage technique, the chiller capacity is reduced to 50% to cool the building during the discharging time from 12:00 pm to 4:00 pm, and the extra cooling is met by the storage tank. In practice this is achieved by increasing the chiller outlet fluid temperature, or by unloading the chiller to a given predetermined percentage of the load. In this operating strategy the control system is complicated, since the peak demand must be met through the storage. Typically, an electric demand meter is used for this purpose [22].

During the night time the chiller starts charging the storage tank at about 6:00 pm and ends at about 2:00 am. The demand limiting operating strategy represents a compromise between full and load levelling partial storage. In addition, the ability to shift the time of peak power demand is higher than for the load levelling system and lower than the for full storage system.

The chiller in the full storage system switches off during the discharging time from 12:00 pm to 4:00 pm as illustrated in Fig. 2 when the building cooling load is directly

met by the storage tank. The discharging time from the storage tank actually begins three hours earlier at about 9:00 am (see the difference between the conventional and full storage profiles) because at this time of the design day, the load on the chiller exceeds the chiller capacity. During the charging period, from 6:00 pm to 4:00 am, the chiller operates at full capacity to produce the required cooling for the building and to charge the storage tank. The full storage system is likely to be attractive if high peak demand charges apply, if there are short overlaps between peak load and peak energy periods or daytime energy rates are based on short duration peak periods [4].

6.2. Power consumption profile

Fig.3 shows a plot of the power profiles of the chillers for conventional and CWS systems. Generally, the power requirement of the chillers increases with the load on the chillers. For a conventional system the maximum power demand occurs during the peak day and is at a minimum during the night time. The power requirements of the conventional system directly increase with load on the chiller during the day time from 10:00 am to a maximum at 3:00 pm and reduce during night the time when the building load is lower. The power requirements reach a maximum of 306 kW_e at about 3:00 pm.

For chillers operating with CWS, except load levelling storage, the power profiles as shown in Fig. 3 have an opposite trend compared to the conventional system. During the night time the chillers produce more cooling and hence consume more power than during the day time. This is because at the night time the chillers in the CWS operate at full load to cool the building and to charge the storage tank. Furthermore, since in the day time between 12:00 pm to 4:00 pm, the building load is met by both the chiller and the storage tank, the power consumption by the chillers is further reduced

as shown in the figure. The degree of power reduction depends on the design operating strategy of the CWS system.

The power profile of the load levelling operating strategy is nearly constant during any one 24 hour period except in the early morning when the storage tank is fully charged and the chiller directly meets the building load. In this operating strategy, the chiller runs continuously at full load to charge the storage tank at night and to meet the building cooling load in day time. Fig. 3 also shows that because of the reduced dry bulb temperature at night, the power consumption of the chiller decreases during the night time compared to the day time, indicating that the chiller operates more efficiently and with higher COP during the night. For a few hours in the early morning, from 4:00 am to 7:00 am, when the storage tank is fully charged, the cooling load is directly met by the chiller further reducing the power consumption. It has been reported in [22] that in this operating mode 40 to 60% of the peak electrical demand for cooling may be achieved during the discharging period.

In the partial storage demand limiting strategy, the power profile of the chiller during charging is similar to that of the full storage system because the capacity of the chillers for the full storage and the 50% demand limiting systems are the same.

However, in the full storage system the storage is greater because more cooling is shifted from the day to night time and the charging period for full storage is longer, as illustrated in Fig. 3. In the demand limiting operation the power reduction that can be achieved depends upon the capacity the chiller is designed to be limited to. Generally, the lower capacity the more power can be time shifted.

Full storage, as shown in Fig. 3, is able to time shift the maximum electrical load.

Compared with a conventional cooling system and other operating strategy, full

storage has been reported to reduce the peak electricity demand by 80 to 90% [22]. For Kuwaiti conditions these values are too optimistic since in an air cooled system and based on the recommended power rating as indicated earlier in this paper, the chiller consumes about 78% of the peak electrical load at peak cooling demand. So with a full storage system, the maximum percentage reduction in the peak cooling electric demand that can be achieved is about 78%.

6.3. Coefficient of performance profile

The results of the COP for the chillers selected in this paper have been carefully analysed. The profile of the COP of the chillers for different operating techniques is shown in Fig. 4. The figure shows that the chiller with a conventional operation has a higher COP during the night time, although the chiller operates at about 40% (e.g. 2 compressors are operating) and is not at full load. It has been found that the average COP during the night time hours (e.g. 6:00 pm to about 4:00 am) is about 2.5 when the chiller operates at an average of 40% full load. However, the average COP during the day time (e.g. from 8:00 am to 3:00 pm) was found to be about 2.0 when the chiller operates at an average of 93% (e.g. three compressors are operating) full load. The high value of the COP during the night time is due to the much lower low dry bulb temperature than during the day time and chillers operating at full load and therefore maximum efficiency.

The chiller in a full storage system does not operate during the discharging hours, therefore the COP is equal to zero as shown in the figure. The chiller with 50% demand limiting has two compressors, when the capacity of the chiller is limited to about 50%, one compressor operates at full load and hence, maximum efficiency. However, because of the high ambient temperature during the day time, the COP is

lower than when compared to the night time period. Similarly, the chiller in a load levelling strategy operates at full load for most of the time and with maximum COP. However, the COP of this chiller reduces during the day because of the high ambient temperature.

7. Discussion

In the following subsections, comparisons of chiller and storage capacity sizes, peak power reduction and energy consumption for the chillers operating with and without CWS system will be discussed. The chillers in an air cooled AC system have the greatest power and energy consumption. The results of the power and energy consumption for chillers with different operating strategies are summarised in Table 2. The power consumption for other auxiliaries such as chilled water primary and secondary pumps and air handling unit motors are not included because further details of air and water distribution design, power and energy consumption are required and are not included in this paper.

The charging storage capacity shown in Table 2 is equal to the storage capacity obtained from Eq. (2) scaled by a factor of 1.1, to account for the thermal losses during the charging cycle of the storage tank, completely recharging the tank and removing the thermocline [7]. The discharging storage capacity in the table represents only the amount of cooling energy required to cool the building during the discharging cycle and a 10% of unusable portion of the chiller water [7] (e.g. if the storage tank is fully discharged, 90% of the usable cold water in the tank will be used, and 10% is the unused portion). Table 2 also include further analysis of the chiller performance in a CWS with a 60% and 70% demand limiting operating strategies and full storage with a larger chiller.

7.1. Chiller and storage sizes

For Kuwait, it is very important to look at the chiller sizes for the different design systems, since they are directly linked to the capital cost of the system and maximum power withdrawn from the utility. The maximum power taken from the utility is directly proportional to the cable connection cost which is very high for the country. The cost of the actual power connection for the Ministry of Energy of Kuwait (the main supplier of electricity) is estimated to be around US\$ 1383 per kW_e [16].

Referring to Tables 1 and 2, it can be seen that load levelling partial storage has the smallest chiller and storage sizes compared to other storage systems. Generally, as given in Table 1, the nominal chiller sizes obtained from Eq. (1) for all chillers operating with CWS, partial load levelling, 50%, 60%, and 70% demand limiting, and full (smaller chiller size) strategies are 33%, 23%, 25%, 27%, and 12% respectively smaller than the nominal chiller size of the conventional system. Therefore, using a CWS system can reduce the initial and maintenance costs of the chiller. The actual percentage reduction in chiller sizes given in Table 2, obtained from the selection program, is smaller than that shown in Table 1, because the program does not guarantee to give the exact sizes for the nominal chillers given in Table 1.

Compared to other storage techniques, full storage has the largest storage capacity, because it has the highest load shifting. The chiller and storage sizes of demand limiting operation represent a middle ground between load levelling and full storage. The maximum power withdrawn from the utility of the full storage system is about 253 kW_e. The last column of Table 2 shows the results of over sizing the chiller and keeping the same storage capacity for the full storage system. The result show that an over sized chiller leads to a larger maximum power withdrawn from the utility and

slightly less cooling withdrawn from the storage tank. Over-sizing the chiller reduces the time requirement for fully charging the storage tank during the charging period.

The chiller operating with partial storage load levelling have the lowest initial cost and conventional and full storage (with the larger chiller) have the highest costs. This is based on a budgetary price quoted by Carrier for screw chillers [16], storage tank costs estimated as US\$ 14.7 per kW_ch [23], and electricity costs estimated as US\$ 1383 per kW_e to the Ministry of Energy.

7.2. Peak power reduction and energy consumption

Table 2 shows that the chiller operating with a partial storage load levelling strategy has a slightly higher kW_ch electrical energy consumption of about 1% compared to the conventional chiller. This strategy has the lowest peak power reduction, of 34%, compared to the conventional chiller. This is because in this operating strategy the chiller is running at full capacity during the discharging hours to meet part of the building cooling load and the rest is met by the stored chilled water.

The peak power reduction of the chillers in the demand limiting partial storage systems varies depending on the proportion of demand limiting that the chillers are designed for. The higher the proportion the less the peak electricity power is reduced. The energy consumption of the chillers in these systems is higher than the conventional system by approximately 2 to 4% and fall between the full and load levelling storage strategies as shown in Table 2.

The chillers (small and large) in the full storage strategy achieved the greatest reduction in peak power, see Table 2. This is because in the discharging time, the chillers are entirely switched off, the cooling load is directly met by the storage tank

all the electrical load is shifted from day to night time period. Furthermore, full storage of a 530 kW_c chiller has the lowest electrical energy consumption. When a larger chiller (e.g. 607 kW_c chiller) is used the energy consumption increases by 5% compared with the conventional chiller and the percentage of storage used slightly decreases from 89% to about 83%. Therefore increasing the chiller size for a given tank size increases the energy consumption and decreases the percentage of the discharging capacity.

The results for the percentage of the peak power reduction of the chillers in Table 2 can be further used to estimate the peak percentage reduction in the peak power of an air cooled AC system when CWS systems are used with different operating strategies. As discussed in Section 4 based on the recommended power rating of an air cooled system, the chiller, chilled water pumps, and air handling unit consume about 78%, 18.5% and, 3.4% respectively of the peak electrical load during the maximum cooling demand period. Therefore, the peak load of an air cooled system can be reduced by 26.5% (e.g. $0.34 \times 78\%$) if a partial storage load levelling strategy design is used. Similarly 50%, 60%, and 70% demand limiting can reduce the peak electrical load of an air cooled AC system by 44.5%, 38.2%, and 36.7% respectively and for full storage by 78%. Therefore, with different CWS operating strategies the percentage peak power reduction of the chiller in an air cooled system can be reduced by up to 78%, depending on the selected CWS operating strategy.

8. Conclusion

The demand for electricity in Kuwait is growing annually at an average of 6.2% because of the continual expansion in building construction, urban development, high subsidised energy cost and the reliance on AC systems for the cooling of buildings. It

has been estimated the AC systems in Kuwait annually consume about 39% of the total generated and 45% of the exported electrical energy. It has also been estimated that approximately 63% of the electricity generation during the peak demand period is consumed only by the AC systems of buildings. In this paper, it has been shown that implementing CWS with different operating strategies in a conventional system can reduce the peak electrical load of the AC system.

For air cooled chillers implementing a CWS system reduces the peak electrical power consumption of the chiller, compared to the conventional system at peak cooling demand, by up to 100% depending on the selected operating strategy, and therefore on the peak electrical load of an air cooled AC system by up to 78%. However, the results have shown that chillers operating with load levelling and demand limiting partial storage strategies have a slightly higher energy consumption of up to 4% compared to a conventional system for the peak design day. Moreover, in the full storage system, the calculated energy consumption of the chiller has been found to be 4% lower than the conventional system. Therefore we may conclude that CWS operating with a full storage strategy is the optimal choice for the Kuwait climate, since both the peak power and the energy consumption of the chiller (e.g. the most significant power and energy consumer in the AC system) can be reduced. In addition for future expansion of the cooling system, the full storage system can be operated as a load levelling or demand limiting partial storage without additional cost.

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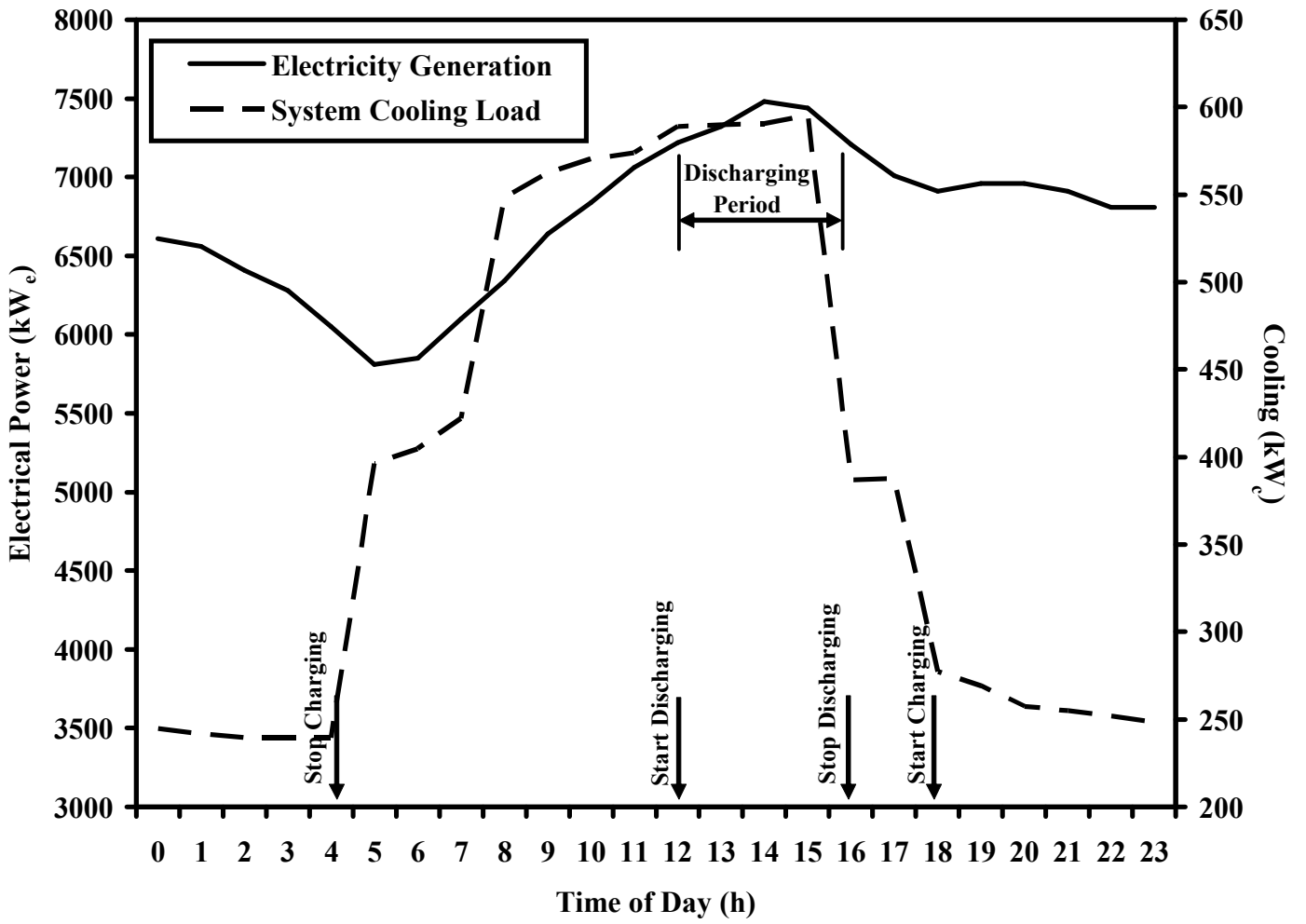


Fig. 1. Selecting charging and discharging hours for a CWS system.

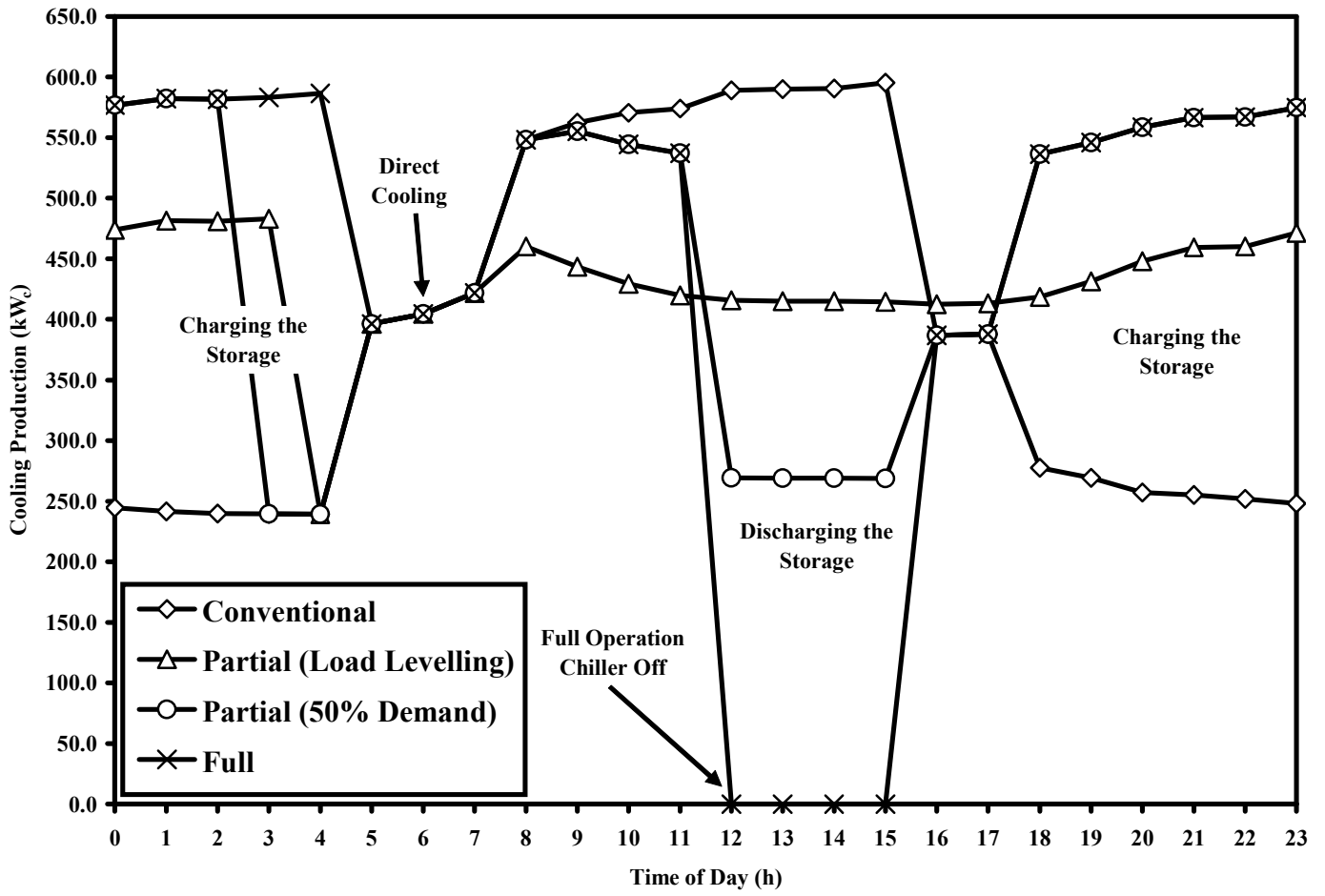


Fig. 2. Hourly cooling production profiles for different operating strategies.

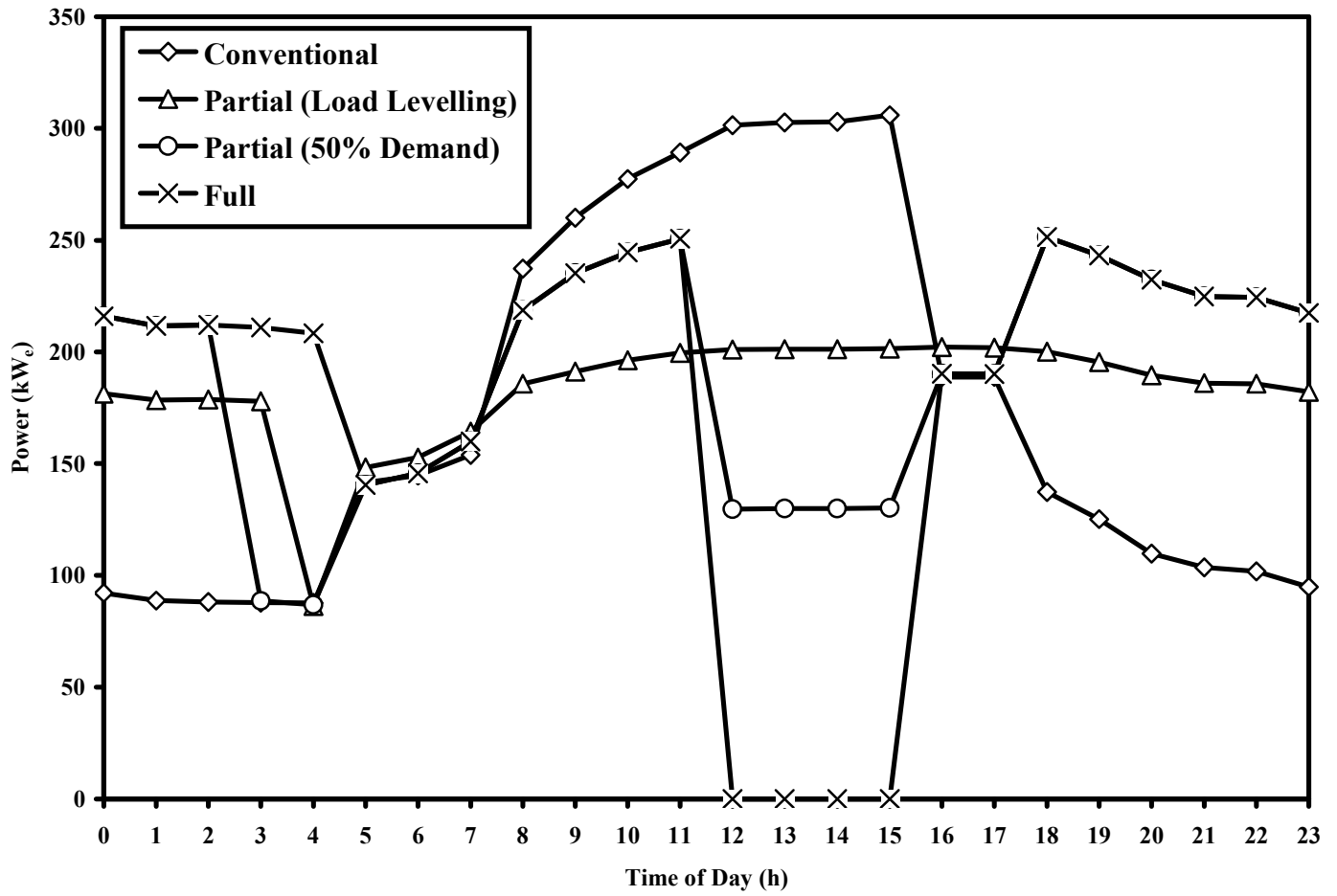


Fig. 3. Hourly power profiles for different operating strategies.

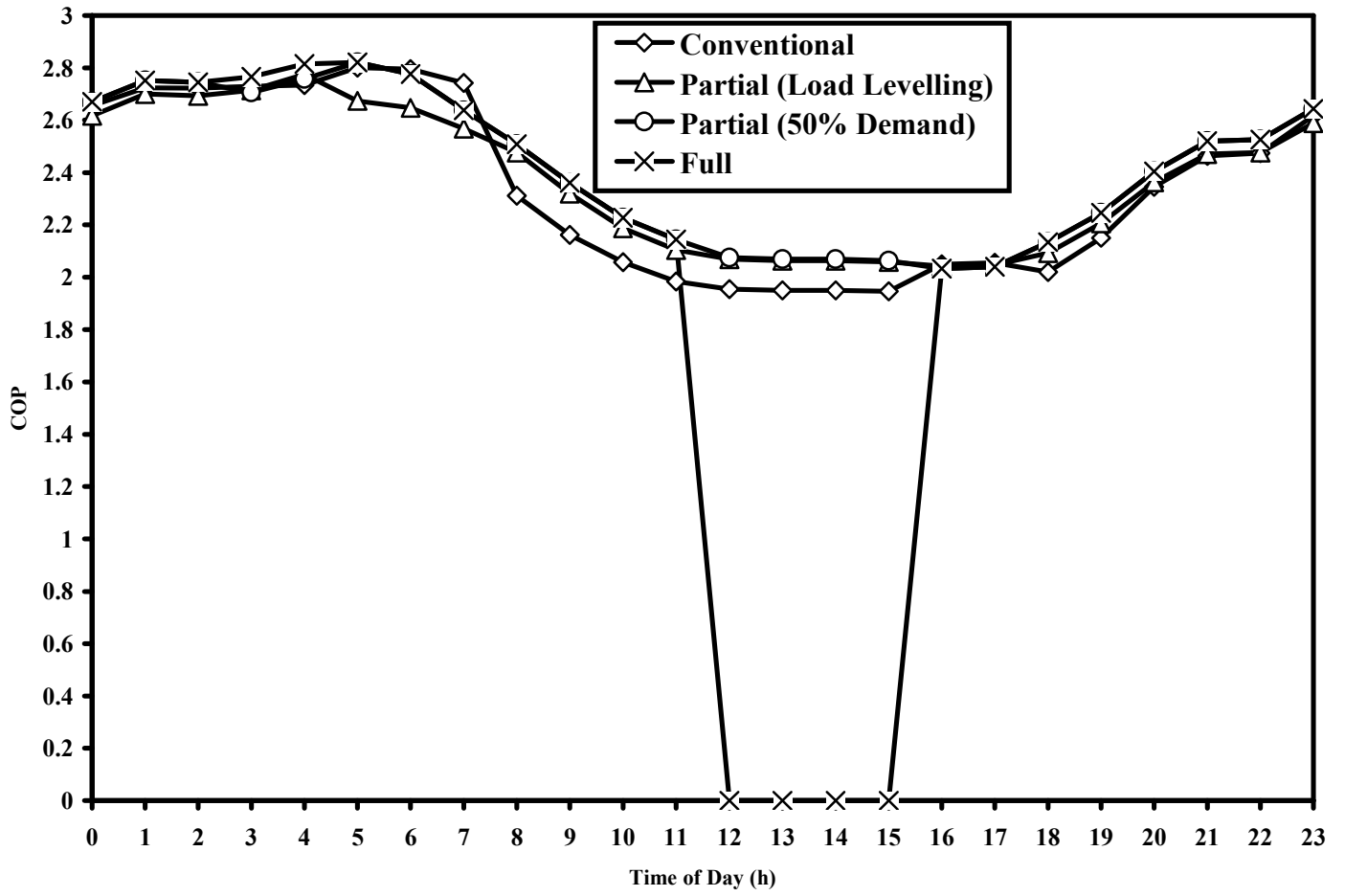


Fig. 4. Hourly COP profiles for different operating strategies.

Table 1 Nominal chiller and storage capacity sizes for different operating strategies

	Partial Storage					
	Conventional	Load Levelling	Demand Limiting			Full
			50%	60%	70%	
Nominal Chiller Size (kW _c)	595.2	397.2	455.7	444.4	433.7	523.3
Increase in Chiller Size (%)	0.0	-33.3	-23.4	-25.3	-27.1	-12.1
Storage Capacity (kW _c h)	0.0	1634.8	2048.4	1935.3	1828.1	2725.4
Storage Volume (m ³)	0.0	138.7	173.8	164.2	155.1	231.2

Table 2 Comparison of results for conventional and CWS operating strategies

	Conventional		Partial Storage			Full Storage	
			Load Levelling	Demand Limiting			
				50%	60%		
Chiller Size (kW _c)	622	410	530	530	435	530	607
Power at Peak Load (kW _e)	306	201	130	155	163	0	0
Chiller Energy Consumption (kW _e h)	4127	4173	4229	4284	4249	3972	4314
Maximum Power (kW _e)	306	202	253	253	218	253	312
Increase in Chiller Size (%)	0	-34	-15	-15	-30	-15	-2
Cool Storage Used (%)	0	81	73	66	92	97	93
Increase in Peak Power (%)	0	-34	-57	-49	-47	-100	-100
Increase in Energy Consumption (%)	0	1	2	4	3	-4	5
Average COP	2.33	2.37	2.40	2.40	2.28	2.48	2.35