ENERGY COMPARISON BETWEEN CONVENTIONAL AND CHILLED WATER THERMAL STORAGE AIR CONDITIONING SYSTEMS

M.J. Sebzali*, Associate Research Scientist

H.J.Hussain, Research Associate

B. Ameer, Research Assistant

Department of Building and Energy Technologies
Environment and Urban Development Division
Kuwait Institute for Scientific Research
P.O.Box: 24885 Safat, 13109 Kuwait
Email: msebzali@safat.kisr.edu.kw

* Corresponding author

ABSTRACT

During the summer of previous years, Kuwait faced a series of power shortages emphasizing the need for urgent commissioning of power generation projects. It is estimated that the demand for electricity is growing at an average of 6.2% per year, encouraged by government subsidies and driven by the rapid and continual expansion in building construction, urban development, and the heavy reliance on Air Conditioning (AC) systems for the cooling of buildings. The Chilled Water Thermal Storage (CWTS) system is one of the available techniques that can be utilized to reduce peak electricity demand of buildings when national electricity consumption is at its highest level.

This paper demonstrates that the use of CWTS system reduces the peak power demand and energy consumption of AC systems for design day conditions by 36.7% - 87.5% and 5.4% - 7.2%, respectively. This reduction depends on selected operating strategies as compared with conventional AC system. Furthermore, results show that the annual energy consumption of CWTS systems decreases by between 4.5% and 6.9% compared with conventional systems, where chillers and pumps significantly contribute to this reduction.

Keywords: peak power demand; cooling demand; Kuwait; air cooled; energy consumption; clinic

INTRODUCTION

Cool thermal storage is a technology that stores “cooling” energy in a thermal storage mass, the storage mass can be a third major component of an AC system in a building. In a conventional AC system, there are two major components: chiller to make chilled water and distribution system to transfer chilled water from the chiller to the Air Handling Units (AHU). There are six major cool thermal storage technologies, chilled water and eutectic salt storage systems use standard conventional water chillers (Dorgan, 1994). These storage technologies have the advantage of being compatible with existing chillers and probably being the most energy efficient storage system. It has the disadvantage of requiring much larger storage tanks than the other storage media. Internal melt ice-on-coil, encapsulated ice, and external melt ice-on-coil systems use standard packaged chillers to cool secondary coolants to ice making temperature. One of the above mentioned storage technologies can be incorporated within AC systems to reduce the peak power demand and possibly the energy consumption of a building. This paper will focus on the use of Chilled Water Thermal Storage (CWTS) system to reduce peak power demand of a clinic in the weather condition of Kuwait.

In the CWTS system, a large storage tank is used to store chilled water at a temperature between 4.0° C and 6.7° C. This temperature is compatible with most conventional AC systems and allows the use of a conventional chiller. The chiller in this system cool the water during the night time when the demand for electricity is low and store it in the tank for later use during day time when the demand for electricity is high. The amount of cooling energy that can be stored in the tank is maximized by maintaining a high chilled water temperature differential.

Higher operating efficiency of the system can be realized with CWTS, because the storage occurs during the night time when lower ambient temperatures improve the performance of heat rejection equipment. Moreover, CWTS operates under the same conditions as for conventional AC systems. Similarly, the piping configuration and AHUs are same as in a conventional system, which makes the design consideration easier (Fiorino, 1991).

Many CWTS systems were installed in USA, to shift the peak electrical power from high demand period, to lower demand period. CWTS AC systems account for 10% of the total cool thermal energy storage capacity, with an average system capacity of 50.3 MW_ch and an average storage tank size of 4804 m^3 (Potter,1995).

The Ministry of Electricity and Water (MEW) in Kuwait, which is the sole supplier of electricity in the country, is deeply concerned about the excessive demand for electricity due to AC consumption. Based on statistical data of MEW (2008), the peak power demand from 1998 to 2007 grew at an annual rate of 5.4% well above the world average of 2.7% (Khatib, 2005). Peak power demand is important because MEW is faced with investing in new generation capacity to cope with expected increase in peak demand. It has been estimated that the AC systems annually consume about 39% of the total electrical energy 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 (Sebzali, 2007).

This paper aims to study the impact of using CWTS system technology on the peak power demand and energy consumption of the AC system of a clinic. The clinic 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 long reception a large glassed areas including a skylight. This building is occupied from 07:00 a.m. to 02:00 p.m. for five days a week, and has a total floor area of 3,200 m^2.

Furthermore, two operating strategies are examined for CWTS systems, partial and full storage strategies. For the partial storage strategy, load levelling (with chiller priority) and 50% demand limiting strategies were examined. In the partial storage strategy with chiller priority, the chiller meets the cooling demand as much as possible and when the cooling demand exceeds the chiller capacity, the additional cooling is supplied from the storage tank. In the full storage strategy, the chiller switches off completely during peak cooling demand and the stored water meets the cooling demand.

In Kuwait, there is no cheap rate electricity tariff and there is no direct cash incentive offered by MEW for demand management measures. However, the CWTS system may be attractive for both end-user and government if peak power demand and energy consumption are both reduced.

PROPOSED CENTRAL COOLING PLANT AND CHILLED WATER DISTRIBUTION SYSTEM DESIGNS

In this study, the cooling production for the central cooling plant of the conventional AC system was assumed to consist of a single electric-driven air-cooled chiller and one working (plus one standby) primary (or chiller) constant flow chilled water pump. The cooling production of CWTS systems is same as conventional system but with additional stratified chilled water tank. Chillers and storage tanks capacities in CWTS AC systems operating with 50% demand limiting and full storage strategies were estimated based on four hours discharging time, starts at 11:00 am and ends at 3:00 pm. It was also assumed that storage charging starts at 6:00 pm. Specifications of the chillers, pumps and storage tank of the AC systems are given in Table 1.

The chilled water distribution systems for conventional and CWTS were arranged with primary-secondary piping designs (James, 1996; ASHRAE, 2000 Chap. 11). This design is considered today the most popular chilled water system because it separates the chiller (that is, the chilled water production zone) from the distribution piping system (that is, the chilled water transportation zone) thereby reducing the differential pressure drop across the control valves of the cooling coil.

Design volumetric flow rate in the primary circuit is met by a single centrifugal pump with a second standby pump of the same size. The primary pump was assumed to be running 24 hours a day irrespective of the load on the chiller. In the CWTS systems, the primary pump was sized to overcome the pressure drop of the extra control valves that are associated with the chilled water tank and the pressure drop in the piping network of the diffusers within the tank. The primary pump was assumed to deliver the required flow rate during both the charging and discharging cycles to the secondary circuit. When the chilled water storage system is at full storage, the primary pump is switched off completely, and the secondary pumps supply the water to the air handling units from the storage tank.

Table 1. AC components specifications.

Specification	Conventional	Chilled Water Storage System		
		Partial		Full
		Load Levelling	50% Demand Limiting	
Chiller				
Number of Chillers	2	2	2	2
Capacity (kW_c) Normal/Charging	422	226	311	334
Power Input (kW_e) Normal/Charging	206	110	143	166
COP	2.04	2.06	2.17	2.01
Flow Rate (L/s)	16.5	5.41	7.42	7.99
No. of compressors	2	2	2	2
Exit Temperature (^oC)	6.67	5.56	5.56	5.56
Inlet Temperature (^oC)	12.78	15.56	15.56	15.56
Cooler Pressure drop (kPa) Normal/Charging	24	9	9	11
Working Fluid	Water	Water	Water	Water
Tank Size (m^3)	-	76	102	146
Primary Pumps				
Number of Pumps	2	2	2	2
Flow Rate Per Pump (L/s)	16.5	5.4	7.4	8.0
Head (m)	11.3	8.8	14.2	11.3
Motor Input Power (kW_e)	2.7	0.9	2.0	1.6
Secondary Pumps				
Number of Pumps	4	4	4	4
Flow Rate per Pump (L/s)	5.6	3.3	3.3	3.3
Head (m)	15.8	14.6	12.4	15.4
Motor Input Power (kW_e)	1.8	1.2	1.0	1.2

The secondary chilled water distribution piping system for both conventional and CWTS systems was arranged with a direct return piping arrangement (ASHRAE, 2000 Chap. 12). This piping arrangement is strongly recommended by most designers for variable flow distribution and where the flow rate through the cooling coil is controlled with a two-way temperature control valve. It is assumed that the chilled water in the secondary piping system circulated by three parallel constant flow secondary pumps (plus on standby). Each pump takes its suction from a common header and discharges into another common header, thus sharing the flow while operating at the same head. This pumping arrangement allows the pumps to be switched on and off as required to meet the varying demand. Each pump operates at the same head, but shares the flow rate with the other pumps. Multiple pumps in parallel can be controlled by either a flow measuring device or by a pressure differential controller.

DEVELOPMENT OF SYSTEM COOLING LOAD PROFILES

The building energy simulation program, ESP-r, was used to determine the cooling demand of the clinic using typical metrological weather data for Kuwait (Clarke, 2001). The simulation was conducted by defining the geometry and the construction of the internal and external walls, roof, ceiling, and ground floor. The boundary conditions for each surface and the operation schedules of the internal load such as occupancy, lighting, and appliances were also defined for each zone of the clinic.

In an attempt to reduce the cooling demand during the night time, the clinic was simulated with defined ventilation control. It was assumed that ventilation starts at 5:00 am and ends at 3:00 pm, at other hours during the day the ventilation was set off. Ventilation control has reduced the total integrated cooling demand during the 24-hour period from 5.7 MWh to 4.3 MWh, This makes the use of CWTS more attractive because of the lower building cooling demand during the time at which the tank is charged.

The system load profiles for CWTS and conventional AC systems were obtained by adding estimated heat gain from auxiliary systems including AHU motors, pump motors, supply and return ducts and chilled water pipes. The heat gain by AHUs was obtained based on calculated design of volumetric air flow rate and pressure drop across the AHUs and ducts, the heat gain by primary and secondary chilled water motor pumps were computed using calculated design volumetric flow rates of the chilled water and the total pumping head, and heat gains by the piping systems were determined using the temperature difference between the chilled water and ambient and overall heat transfer coefficient. The developed systems load profiles is plotted as shown in Figure 1.

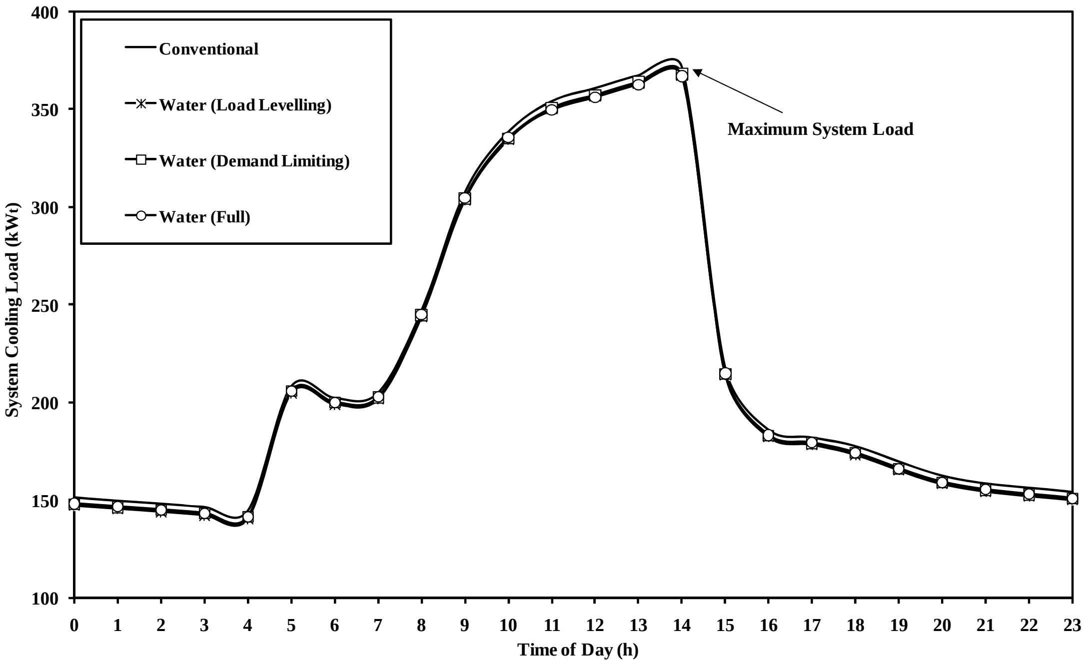

Figure 1. Hourly system load profiles of the AC systems.

It can be seen from Figure 1, that the differences in system load profiles is minimal. This is because the building cooling demand is the same in all AC system designs and the differences in the profiles stems mainly from the differences in the heat gains by the auxiliary systems. The heat gains of auxiliary systems in CWTS were found to be slightly lower than in the conventional AC system due to smaller sizes of motor pumps.

ESTIMATED POWER DEMAND

The performance data of the chillers in CWTS and conventional AC systems were obtained using Carrier ECAT2 (Carrier, 2004). The performance data including percentage load, gross capacity, absorbed power and COP are based on a factory run test for each chiller model at the full load design and part load operating points as required. The power demand of the chillers was established using the design day dry bulb temperatures of Kuwait AND developed system cooling loads.

The power demand of AHU motors was obtained from the FLEX-air Version 5.08SA software program (Carrier, 2005), based on the calculated pressure drop and design volumetric flow rate of air as well as fans and motors efficiencies. In addition, it was assumed that the AHU motors would run continuously throughout the year irrespective of the cooling demand of the clinic; thereby, the motors would run at a constant speed.

Similarly, the power demand of primary and secondary pump motors was estimated base on estimated design pressure drop, chilled water volumetric flow rate, pumps and motor efficiencies. Primary chilled water pump (e.g. chiller pump), was assumed to be running continuously at constant speed only when chiller is in operation. In case of secondary chilled water pumps, the power demand was determined based on the number of pumps that come into operation. The number of pumps is a function of the volumetric flow rate of chilled water circulating through the cooling coil, which varies depending on building cooling demand.

RESULTS AND DISCUSSIONS

Chillers's Cooling Production

Figure 2 illustrates hourly cooling production profiles for conventional chiller and for chillers in CWTS operating with load levelling, 50% demand limiting partial storage and full storage strategies.

In the conventional AC system, the chiller directly meets the cooling demand of the clinic, hence the shape of the profile is similar to the profile of the developed system cooling load. The chiller runs 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.

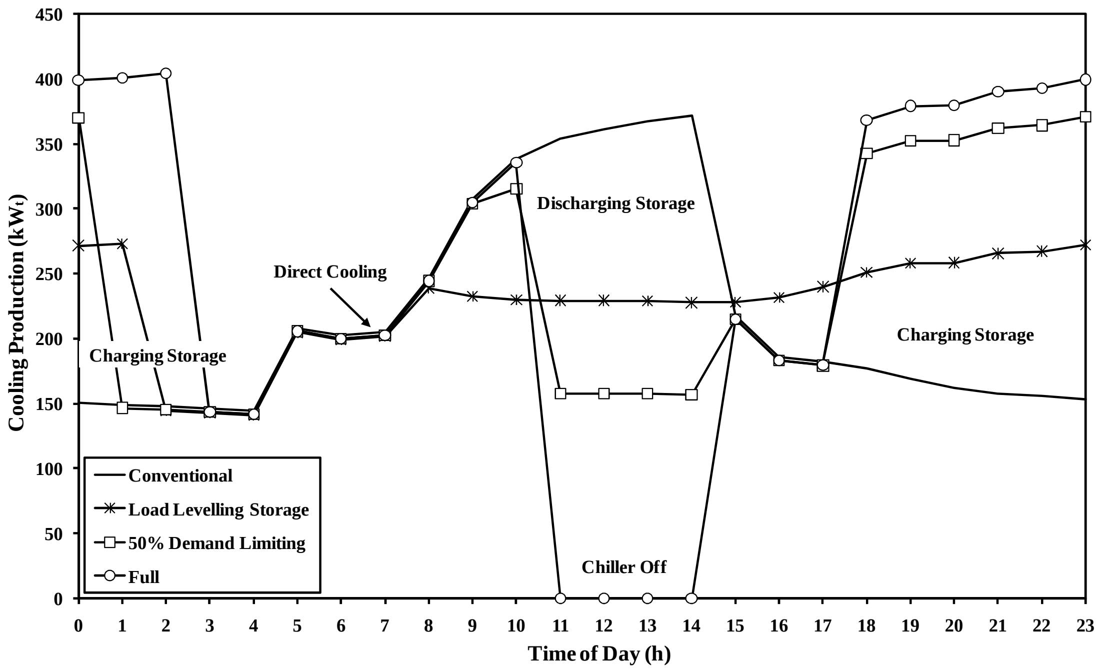

Figure 2. Hourly cooling production profiles of chillers.

Chiller in load levelling operation strategy runs at full capacity for most of the time on the design day. When cooling demand is less than the chiller capacity, the excess cooling is stored in the tank; when the cooling demand exceeds the chiller capacity, the additional requirement is discharged from the tank. In 50% demand limiting partial storage, chiller operates at 50% reduced capacity from 11:00 am to 3:00 pm and extra cooling requirement is met by the stored chilled water. In practice, this can be achieved by passing 50% of the chilled water produced by the chiller through the secondary circuit and back to the chiller again using a two or three way valve. With full storage, the chiller is completely switched off during the discharging time and the entire cooling demand is met by the stored cooling. During the charging time, from 6:00 pm to the time when the storage tank is fully charged, the chiller is operated at full capacity to meet the cooling demand of the clinic and simultaneously to charge the tank.

Chillers's Power Demand

The hourly power demand profiles of the chillers are shown in Figure 3. It can be noticed from the figure that the power requirement of conventional chiller directly increases with cooling demand of the clinic (that is, load on the chiller). At about 2:00 pm the power is at its peak. The peak power demand of the chiller in conventional chiller AC system is higher compared with chillers in CWTS. For chillers operating with CWTS, except load levelling strategy, the shapes of the power profiles have an opposite trend compared to the chiller in the conventional AC system. During the night time, the chillers operate at full load hence consume more power for most of the time to produce enough cooling to meet cooling demand and simultaneously charging the tanks. Furthermore, since in the day time between 11:00 pm to 3:00 pm, the cooling demand is met fully or partially by the storage tank, the load on the chillers decreases, hence the power demand as shown in the figure.

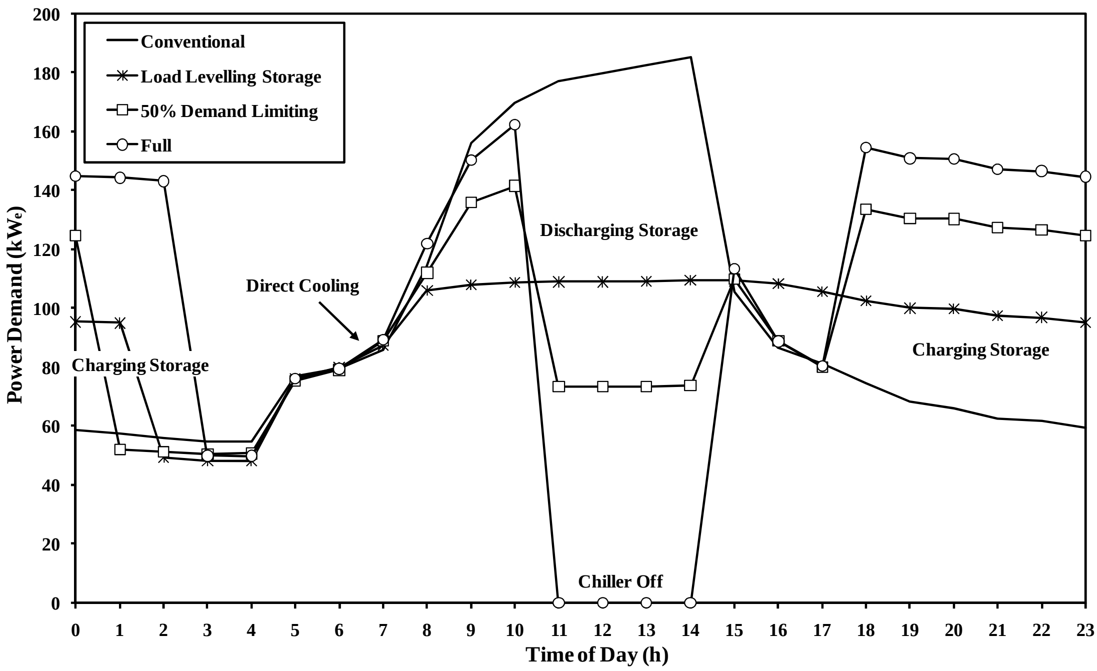

Figure 3. Profiles of hourly power demand of chillers.

Furthermore, it can be observed that full storage shifts maximum electrical load compared with a conventional AC system and other operation strategies. During the discharging time, from 11:00 am to 3:00 pm, the chiller in the full storage is entirely switched off, and all cooling demand is directly met from the stored water in the tank. In full storage, the chiller and storage sizes are larger than those of other operating strategies. In partial storage strategies, the power demand is partially shifted. The lowest power demand is shifted when load levelling strategy is implemented, however, in this design strategy, the chiller and storage sizes are lowered hence lower capital cost. The power shifting in 50% demand limiting approach represents a middle ground between full and load levelling strategy. The power reduction that can be achieved with this approach depends upon the capacity to which the chiller is designed to be limited. Generally, the lower the capacity, the more power that can be shifted.

Comparison of Energy Performance of CWTS and Conventional AC Systems

It is well known that chilled water storage systems can reduce the power demand during the day time when the power load of a conventional AC system is high. However, the amount of the reduction in the power that can be achieved when using storage systems differs from one operating strategy to another. Furthermore, another important factor that must be considered is the amount of increase or decrease in the energy consumption for each component as well as the overall energy consumption, because the operating cost increases with increasing energy consumption.

In the following subsections, one of the main objectives of this study is discussed, namely, the change in power and energy consumption for each component and the overall energy consumption between the conventional and chilled water storage systems.

Power demand

The change in peak power demand of various components in CWTS compared to conventional AC system at design day is shown in Figure 4. The peak power demand occurs at about 2:00 pm when the cooling demand is at its maximum. The overall reduction in the peak power is achieved with the full storage strategy where power has decreased by 87.5% compared with conventional AC system. This lies within the range of 80 to 90% estimated by (Hasnain, 1998). Furthermore, load levelling operating strategy had the lowest reduction at 36.7%, and the reduction in 50% demand limiting strategy is 54.2%, somewhere between full and load levelling strategies. The high reduction in the overall peak power demand for full storage strategies was established mainly from the chiller and pumps.

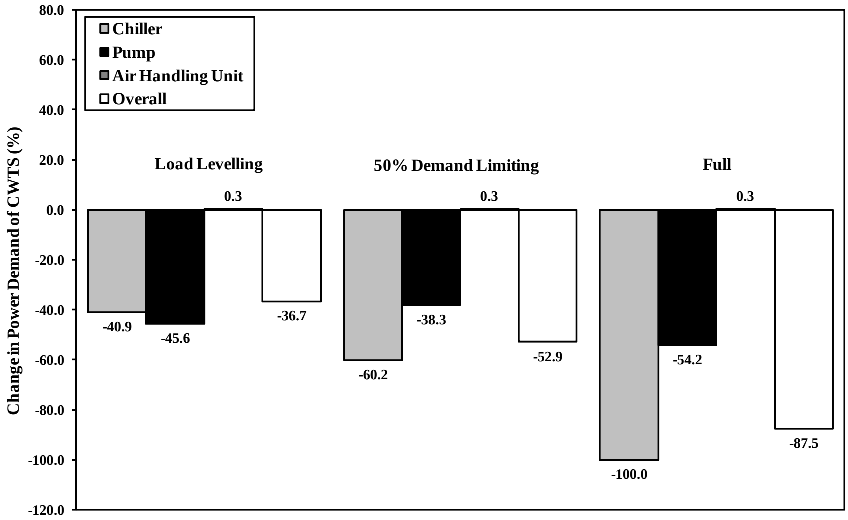

Figure 4. Change in the power consumption of CWTS systems with conventional system.

Figure 4 also shows that the reduction in peak power demand by the pumps of the CWTS ranges from 38.3% to 54.2% depending on the operating strategy. The reduction in pumping power resulted mainly from lower designed volumetric flow rate of the chilled water in the primary and secondary piping circuits compared to conventional AC system. Moreover, it can be observed from the figure that the peak power demand of the AHUs in CWTS is slightly higher than conventional AC system therefore; they have minor effect on the overall peak power demand.

Annual energy

The annual energy consumption is one of the most important factors that affect annual operating cost. Therefore, it is very important to examine the change in its value when CWTS is implemented. The change in annual energy consumption for each component of CWTS AC systems is plotted in Figure 5. The figure demonstrates that the overall energy consumption is established for all operating strategies. It is clear that the highest reduction is 6.9% realised with a 50% demand limiting strategy, mainly contributed by reduction in the energy consumption of chiller (9.1%) and chilled water pumps (36.6%). The high reduction in energy consumption of the chiller was mainly due to higher COP (2.17) of chiller model in this strategy.

The reduction in the overall annual energy consumption for the load levelling strategy is 6.3% and for the full storage operating strategy is 4.5%. In addition, the energy consumption of the pumps in the load levelling strategy is reduced by 50% compared with that of the pumps in the conventional system. It is also clear from Figure 5 that the AHUs have the least effect on the annual energy consumption; they have increased the consumption by only 0.3%.

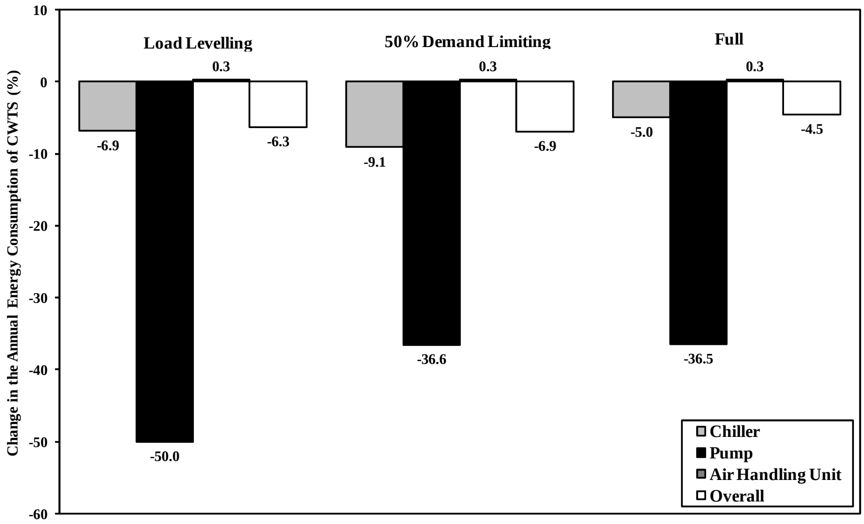

Figure 5. Change in the annual energy consumption of CWTS compared with that of the conventional system.

CONCLUSION

The power demand and energy consumption of CWTS and conventional AC systems for a clinic were estimated and analysed using design day dry bulb temperature and typical metrological year of Kuwait. In addition, the power demand for each component in the AC systems was examined. It have been shown that CWTS shifted peak power demand by between 36.7% and 87.5%, and reduced the annual energy consumption by between 4.5% and 6.9% depending on the selected operating strategy.

Therefore, it can be concluded that CWTS incorporated within conventional AC system is good storage option for cooling of buildings in the Kuwaiti climate. Since both the peak power demand and annual energy consumptions were both reduced. However, for optimal choice of storage technology and operating strategy, life cycle cost analysis must be conducted taking into account capital and operating costs and project life time to further demonstrate the applicability of such technology for Kuwait.

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