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Suitability of district cooling for Kuwait

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1. Introduction

National peak power demand and annual electricity consumption in Kuwait is increasing with an annual rate over 5% (MOE, 2005) due mainly to air-conditioning (A/C) of residential sector. Most A/C units used in residential sector use rooftop DX-units with air-cooled condensers, which are not so efficient as the peak summer temperature often soars to over 50^{o} C during the long summer period of eight months.

District Cooling (DC) is an excellent way to achieve high energy-efficiency and large power shaving in the dry and hot weather of Kuwait. A DC system uses large capacity chillers with water-cooled condenser (WC) and centrifugal or screw compressors to produce cooling efficiently and save peak power and energy. A DC system with chilled water cool storage can further cut down the peak power demand on electrical utilities.

There has been a worldwide growth in adapting DC systems over the past decade including some of the Middle East countries. Recently, DC schemes are rapidly gaining increasing market share in the United Arab Emirates and the wider Gulf Cooperation Council countries (Naylor, 2005).

This paper explores the use of a DC system as energy efficient and cost effective alternative cooling system for a newly developed residential complex in Kuwait.

2. Description of Residential Complex

Block 1 of South Doha residential complex for which the DC system has been taken as a case study has 466 houses, two mosques and a school. The estimated cooling demands of each of these dwellings are 30, 100 and 150 RT, respectively. The houses with a total share of 97% are the largest contributor to the total cooling load of 14330 RT. For conventional system with unitary units for individual users, the total installed capacity for the A/C system will be 14330 RT. Commonly used unitary units for houses are package units (PU) of 10-40 RT capacity. For the DC system, besides the cooling demand of these buildings, there is additional heat gain from the chilled water pumps, chilled water piping, and the air distribution fans.

3. Engineering-Economic Analysis

Present analysis envisages use of Straight Line Method (SLM) for comparative evaluation of conventional and DC systems. The SLM combines annual amortized value of initial cost (AAIC) over the life-cycle (n) and the annual operating cost (AOC) to give the annual cost (AC) of a system. The initial cost (IC) is the summation of the installed cost of the A/C system and associated electric work in the plant room (CP) and the utilities, such as electricity generation plants (CE) and water desalination units (CW).

$$AC = AAIC + AOC \quad KD/yr \qquad (1)$$

$$AAIC = CP * CRF_{CP} + CE * CRF_{CE} + CW * CRF_{CW} \quad KD/yr \qquad (2)$$

For the discount rate (i) and the life cycle (n), the cost recovery factor (CRF) is estimated as:

$$CRF = i * (1+ i)^n / (1+ i)^n - 1 \qquad (3)$$

AOC included the cost of electricity (SE), water (SW) and other miscellaneous (SMISC) items consumed by the A/C system, with the cost of annual operation (O) and maintenance (M) including the spares. Assuming that AOC is uniform over the life cycle of the A/C system, it is estimated as:

$$AOC = SE + SW + SMIC + O + M \qquad KD/yr \qquad (4)$$

Scope of the study has been confined to cooling production and cooling distribution subsystems.

3.1 Engineering Analysis

Engineering Analysis is concerned with estimation of maximum system cooling capacity for the design conditions (PSCD), and its power requirement for the peak hour (PP) besides the annual or seasonal consumption of electricity (E) and water (W).

3.1.1 System Cooling Demand

System cooling demand (SCD) is the cooling delivered by the system at an instant of time. System cooling capacity under design conditions (PSCD), is estimated after accounting for the heat gain from different auxiliaries used for cooling distribution, such as chilled water piping, chilled water pump motor, air ducting and air fan motor, besides the cooling demand of the building (BCD) for the design conditions (PBCD). Although PBCD, the combined cooling demand for all buildings is same both for conventional and DC system, a DC system helped by the diversity factor (DF) of the buildings at the time of peak cooling demand facilitates opting for a smaller cooling system as compared to the conventional system. For the centralized cooling production and distribution of DC system, a DF of 0.8 has been assumed. Thus, the DC system will be designed to feed only 11464 RT for cooling to the buildings, although it will have air distribution system for 14330 RT similar to the conventional system.

Accordingly, based on the peak building cooling demand, the PR for the AHU fan motors is 0.215 kW/RT and for a PBCD of 14330 RT, the heat gain from the fans of AHUs is 3081 kW (876 RT). Also, the heat gain in the air ducting of 215 RT. These gains are same both for conventional and DC systems. The DC system has additional heat gains of miscellaneous chilled water pumps and chilled water piping. Estimated power consumed by the primary (365 kW) and secondary-tertiary chilled water pumps (1210 kW) will contribute to a heat gain of 448 RT in addition to heat gain in the piping network based on the actual layout of 53 RT. Accounting for these heat gains, the required cooling capacity of the conventional and DC systems are 15421 and 13056 RT, respectively. Thus, the DC system with an installed capacity of 15.3 % less as compared to the conventional system will meet the cooling requirement of the complex.

3.1.2 Peak Power Demand

Conventional A/C system for houses, mosques and school is assumed to be using package units (PU) with air-cooled condensers. Accordingly, the power demand of the conventional system (PD_{conv}) is the sum total of power for the compressor (P_c), condenser fans (P_{FD}) and air-handling unit fans. Although, the system has an installed capacity of 15421 RT, at no point in time, it will be producing a cooling of more than 12555 RT. Based on the condensing unit power rating of 1.5 kW/RT, and accounting 3081 kW for the AHU fan power, the peak power demand of the conventional system is 21914 kW.

Power demand of the DC system is the sum total of power for the chiller (P_{chi}), condenser water pump (P_{cwp}), cooling tower fan (P_{ctf}), besides the P_{ahu}, and P_{chwp}. Based on a PR of 0.7, 0.04 and 0.06 kW/RT for the chiller, condenser water pump and the cooling tower fan, respectively (Maheshwari et-al, 2000), the power demand of the cooling production system without the primary chilled water pump is 10445 kW for a cooling production of 13056 RT. The power demand of primary, secondary and tertiary chilled water pumps is 1575 kW and it is generally unchanged unless motors of these pumps are driven by variable speed drives. Thus, the total power demand of the DC system including 3081 KW for the AHUs is 15101 kW. Accordingly, the peak power demand for the DC system is 31.1% less than that of the conventional system.

3.1.3 Annual Energy and Water Consumption

Period between 1st of March and 30th of November, a total of 6600 h was considered the cooling season in Kuwait and it was assumed that comfort conditions were maintained around-the-clock with constant amount of air circulation. Furthermore, as cooling load of the villas is 97% of the total load, it is assumed that cooling demand for the whole complex follows the pattern of a villa. The seasonal energy requirement was estimated as the product of seasonal cooling production and seasonal power ratings of different components of A/C system.

3.1.4 Seasonal Cooling Production

Using Esp-r, an energy simulation program for buildings, along with the typical meteorological year of Kuwait, seasonal building cooling demand for a villa for a total period of 6600 h was estimated to be 2446 RTh/RT (Mulla Ali and Maheshwari, 2000). Thus, for the present analysis, the seasonal cooling requirement of the buildings is 35.05 million RTh/y. Further, the seasonal cooling production (SCP) was estimated after accounting for the heat gain from miscellaneous cooling production, cooling distribution and air distribution systems. As the heat gain from these systems are different for the conventional and DC systems, the seasonal cooling production of the two systems are likely to be different. The seasonal cooling production for the conventional system (SCP_{conv}) is 41.45 million RTh/y assuming air distribution fans of 3081 kW are in operation during the full cooling season, and heat gain in the ducting is 1.5%.

For a DC system, it is a fair assumption that PR for primary chilled water pumps ($PR_{chwp-primary}$) is constant through out the season since the number of the pumps in operation is directly related to number of chillers in operation. However, regardless of cooling demand of the buildings, all the secondary and tertiary chilled water pumps have to be in operation if the chilled water system is designed on a constant flow. In such a situation, the seasonal PR will be significantly higher than its design value of 0.093 kW/RT, as these pumps will be operating at constant flow consuming 1210 kW regardless of the cooling demand of the buildings, which has an annual average of 37%. This will increase the $PR_{chwp-secondary,tertiary}$ to over 0.25 kW/RT. However, considering the present trend and need for energy efficiency, it is assumed that the DC system will be designed on constant temperature basis adjusting the chilled water flow though the secondary and tertiary pipes in proportion to the cooling demand. This will not only achieve reduction in chilled water flow with the load, the reduced flow will reduce the pressure drop in the system, thereby facilitating pumps operation at lower lifts. It is assumed that this will reduce the seasonal pump head requirement by 25%, accordingly the seasonal $PR_{chwp-secondary,tertiary}$ has been fixed at 0.07 kW/RT. Heat gain in the piping network of 53 RT for the design conditions was 0.4% of the peak cooling production of 13056 RT.

Seasonal cooling requirement for the DC system estimated to be 41.98 million RTh is only 1.3% more than the SCP_{conv}. This small increase which account for the heat gain from primary, secondary and tertiary chilled water pumps and the chilled water piping can be achieved only by using variable speed drives for secondary and tertiary chilled water pumps and using high quality insulation for the chilled water piping.

3.1.5 Seasonal Energy Consumption

For the present analysis, seasonal PR of 1.058 kW/RT has been used against 1.5 kW/RT for the design conditions. Accordingly, the seasonal electricity requirement for operating the condensing units of all the package units to produce 41.45 MRTh of cooling is 43874 MWh/y. Additionally, 20335 MWh/y is to be consumed by air distribution fans during 6600 h at a uniform rate of 3081 kW. Thus, the total seasonal energy consumption of the conventional system is 64209 MWh/y.

Power rating of the chiller with water-cooled condenser to be used in DC system ($PRWC_{chil}$) is a function of incoming condenser water temperature and its loading. For the present analysis, seasonal PR of 0.521 kW/RT has been used against 0.7 kW/RT for the design conditions. Using the seasonal PR for cooling production auxiliaries (chilled water primary pumps, condenser water pumps and cooling tower fans) of 0.128 kW/RT and for cooling distribution (secondary and tertiary chilled water pumps) of 0.07, the seasonal electricity consumption for production and distribution of 41.98 million RTh of cooling is 30184 MWh. Additionally, 20335 MWh/y is to be consumed by air distribution fans during 6600 h at a uniform rate of 3081 kW same as in case of conventional system. Thus, the total seasonal energy consumption of the conventional system is 50519 MWh/y. Seasonal electricity consumption of a DC system is 21.3% less than the conventional system. More importantly, reduction in the seasonal electricity consumption for the cooling production and distribution system is well over 30% since air distribution system is similar in both cases.

3.1.6 Seasonal Water Consumption

For WC systems operating in Kuwait, water consumption in C/T is important because fresh water is not available in nature. Water consumption is dependent upon the heat rejection in the condenser, which is the summation of the compressor power input and SCD. For the present analysis, using the 41.98 million RTh for SCP for DC system and 0.521 kW/RT for the seasonal average power rating for the compressor, the SHR is 48.20 million RTh or 169.51 million kWh. Using the latent heat of vaporization of water (h_{fg}) at 40°C of 2405.9 kJ/kg, the water requirement is 253.6 million kg. Accounting additional 25% water consumption for blow down, the seasonal water consumption is 317.1 million kg.

3.2 Economic Analysis

Economic analyses involve assessment of initial cost and annual running cost. The former is often referred to as capital cost (IC).

3.2.1 Initial Cost

The cost of an A/C system, its electrical work and associated infrastructures and the cost of the power plant and its distribution network required to operate the A/C system are two major contributors to the initial cost. The cost of the desalination plant is an added factor for the DC system, which uses water-cooled condenser. However, the present analysis is conducted using the data for actual cost of water production, which accounts for the cost of desalination equipment.

The conventional cooling system comprises only the condensing unit of the package unit or the ducted split system. It can be designed with alternative schemes with single and multiple condensing units to meet the peak cooling demand of a given building. The installed cooling capacity is likely to be more than the estimated cooling demand as exact size unit may not be available. Also, conventional cooling systems with package units generally have no stand by. In case of DC cooling system, the cooling production system necessarily comprises chillers with water-cooled condensers. A number of large chillers of 1000 RT and above capacity can meet the peak cooling demand of the complex. Generally, during the peak cooling demand hours the chillers operate at full capacity. Besides a minimum of one chiller is recommended as a standby to ensure a trouble free operation, especially during the peak summer season. The unit cost (UC) of installed capacity i.e. KD/RT (1KD=2.7 Euro) was chosen as a cost parameter for comparison for different types of systems.

Based on actual quotations received from two leading manufactures of package units, one local and one American, unit cost for different capacity for the two make were established. In the capacity range of 7 to 13.0 RT, the average unit cost of the local make was 105 KD/RT while for a capacity range of 1-30 RT, its average value for the American unit was 155 KD/RT. Considering that both local and American A/C units are equally popular in the country, an average cost of 130 KD/RT has been assumed for the condensing unit. The cost of the installed unit in operation has been fixed at 200 KD/RT after adding 30KD/RT for the electrical work and 40KD/RT for installation of the unit.

Cost estimates for the district cooling production sub-systems include the cost of the chillers at the site, including its installation, cost of auxiliary equipment for the chillers and the cost of associated electrical work. It is assumed that the present system will have 7 chillers, each one of 2000 RT cooling capacity. These seven chillers will deliver a maximum cooling of 13056 RT with a safety margin of nearly 7% and an additional chiller of the same capacity will be installed as stand bye. Each of these eight chillers will have a condenser water pump, cooling tower, chilled water primary pump and necessary condenser water and chilled water piping, fittings and controls. The UC of Carrier WC chiller with centrifugal compressor for a 1000 RT capacity is 108 KD/RT. Also, the UC of the auxiliary equipment associated with the WC system is 48 KD/RT. Out of this roughly 33 KD/RT is for the cooling tower and 15 KD/RT is for the condenser water pump sets and its piping and fittings. The cost of the primary chilled water pump sets and its piping and fittings has been taken to be 15 KD/RT. Also an additional 30% has been added to this for the insulation. After accounting for an additional 10% of cost for installation of chillers, the unit cost of the cooling production system for a DC system is 187 KD/RT.

Electrical work for the cooling production plant room of the DC system includes the motor control center, starters for various motors and in-house cable work between the motor control center and A/C units. The cost of electrical work is estimated to be 25 KD/kW and the cost (KD/RT) is estimated to be 21KD/RT considering the power rating of the chiller along with its auxiliaries in the plant room is 0.828 kW/RT. Associated infrastructures may include plant room, transformer room, water storage tank, chemical treatment plant and sand filter for the make up water requirement of the cooling tower. All this may cost an additional amount of 52 KD/RT (Maheshwari et, al, 2003). Accordingly, the cost of the cooling production system, its Electrical Work and associated infrastructures is 260 KD/RT. Initial cost parameters for different components of the conventional and DC systems are given in Table 1. Further the current power tariffs in Kuwait have no additional charges for the peak-period power, although it is estimated to cost around KD 400/kW to Ministry of Energy. Instead, in Kuwait, MOE charges the consumer for cable connection @ KD 50/kW and the same has been taken as the peak power cost for the consumer.

Table 1. Unit Cost Parameters for Conventional and DC Systems.

Parameter	**Value**
Conventional; KD/RT	
Condensig unit	130
Installation cost	40
Electrical work	30
Total	**200**
District Cooling; KD/RT	
Chiller	108
Chiller installation cost	11
Cooling tower, pumpsets, piping, fittings and controls for condenser water	48
Chilled water pumpsets-primary, piping, fittings and controls for chilled water with insulation	20
Eelctrical work	21
Infrastructure	52
Total	**260**
Secondary-tertiary chilled water pumpsets and cooling distributin piping and controls; KD/RT	150
Interface with buildings; KD/RT	20
Power cable connection; KD/kW	50
Power plant cost; KD/kW	400

3.2.2 Total Initial Cost

It combines the installed cost of the cooling production and cooling distribution along with the cost of the power plant and power distribution network. Results summarized in Table 2, clearly indicate that a DC system is not beneficiary to the user as far as the initial investment is concerned. A user in Kuwait has to pay nearly 45% more for a DC system as compared to a conventional system with package units. However, DC is beneficiary to the nation, as it reduces the peak power demand considerably that helps to reduce the national cost by over 5%. This reduction in national cost is based for a cooling distribution cost of KD 150/RT. Cooling distribution system of a DC is very much site dependent and an estimation of price of this component is very important and critical. The cost can differ significantly from one site to the other, depending upon the load density (RT/m^2).

Table 2. Total Initial Cost for Conventional and DC Systems for the Nation and the User in Kuwait.

S.No.	Parameter	Conventional	DC	Remark
1	Cost of cooling production system;KD	3,084,193	3,391,940	
2	Cost of cooling distribution system; KD	-	1,958,395	
3	Cost of building inerface; KD	-	261,119	
4	System cost without power; KD	3,084,193	5,611,454	81.9 % more
5	National Electrical cost;KD	7,402,064	4,324,136	41.6 % less
6	Customer Electrical cost;KD	1,310,620	755,065	42.4 % less
7	Total national cost;KD	10,486,257	9,935,590	5.3% less
8	Total customer cost; KD	4,394,813	6,366,519	44.9 % more

3.2.3 Seasonal Cost of Cooling

Seasonal cost of cooling is estimated based on the parameters summarized in Table 3. Results of seasonal cost of cooling are summarized in Table 4. It is 8.5% less in case of DC as compared to the conventional system.

4. Conclusions and Recommendations

1. Installed capacity of the DC cooling system is 15.3% less as compared to the conventional cooling system. However, it has 4% more cooling production during the peak demand period.
2. Peak power demand of the DC system is 31.1% less as compared to the conventional cooling system while it needs cable connection of 43.4% less capacity.
3. Seasonal energy requirement of DC cooling system is 20.6% as compared to conventional system. However, it has additional requirement of substantial amount of fresh water. The energy cost of this water production based on the multi stage flash technology; currently in practice in Kuwait is 11.0%. Accordingly, the effective reduction in energy consumption is 9.6%. This will result is similar reduction in the thermal pollution and other greenhouse gasses emissions in the power plants. Use of seawater for condenser cooling should therefore be explored.
4. The initial cost of DC system along with the cost of the power plant needed to operate the system is 5.3% less as compared to the conventional system. However, as the power in Kuwait is heavily

subsidized and a user pays only 12.5% of the actual cost of the power plant, the situation is not favorable for the DC system. Based on the current power tariffs, a DC system will cost 44.9% more to the user.

5. Based on the actual cost of electricity and water production, the seasonal cost of cooling for the DC system is 8.5% less as compared to the conventional system.

Table 3. Cost Parameters used for the Seasonal Analysis.

Parameter	Conventional	DC
AC system life; yrs	14	23
Discount rate; %	5	5
Power plant life	30	30
Electricity cost to consumer KD/MWh	2	2
Electricity cost to MOE KD/MWh without power plant cost	16	16
Water cost to consumer KD/million l	176	176
Water cost to nation KD/million l, including cost of desalination equipment	640	640
Cost of water treatment KD/million l	165	165
Cost recovery factor for cooling production and distribution	0.101	0.074
Cost recovery factor for power plant	0.065	0.065
Annaul maintenance cost with spares A/C; KD/RT	14	5
Annaul maintenance cost distribution; %	0	0.8
Annaul maintenance cost building interface; %	0	0.8
Annual operation cost	0	49000

Table 4. Seasonal Cost of Cooling for Different Parameters.

S.No.	Parameter	Conventional	DC	Remark
1	Cooling production and distribution	311,577	416,015	33.5 % more
2	Power plant and power distribution network	481,515	281,291	41.6% less
3	Cobined cooling system and power	793,092	697,307	12.1% less
4	Electricity	657,740	518,742	21.1 % less
5	Water	0	205,948	
6	Maintenance, cooling production	215,894	65,280	
7	Maintenance, cooling distribution	-	15,667	
8	Maintenance, interface	-	2,089	
9	Operation	-	49,000	
	Total	2,459,818	2,251,339	8.5% less

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