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Retrofitting the combined-cycle producing electric power and desalted seawater to include district cooling in GCC

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ABSTRACT

Recent installed power plants (PP) in Qatar and other Gulf Co-operation Countries (GCC) are using combined cycle (CC). The CC cycle consists of gas turbine (GT), heat recovery steam generators (HRSG), and steam turbine (ST). In these plants, GTs produce electric power (EP) and its exhaust hot gasses operate the HRSG to generate steam. The steam is supplied to ST that generates more EP, and its extracted (or discharged) steam is directed to thermally operated desalting plant (DP), e.g. multi stage flash (MSF) or multi-effect thermal vapor compression (ME-TVC) producing desalted seawater (DW). A plant producing both EP and DW is called co-generation power desalting plant (CPDP). The used ST type is either extraction condensing steam turbine or back-pressure steam turbine. The MSF or ME-TVC consumes about 280 MJ/m^3 thermal energy, besides pumping energy of 4 kWh/m^3 for MSF or 2 kWh/m^3 for ME-TVC systems. Because of high consumed energy, the MSF and ME-TVC systems have to be substituted by the much more energy-efficient seawater reverse osmosis (SWRO) desalting system, which consumes 4–5 kWh/m^3 only as pumping energy. Replacement of the MSF (or ME-TVC) with the SWRO system will ban the use of steam extracted (discharged) to the DP; the plants produce only EP, and become single-purpose PP. This reduces the plant overall efficiency unless major retrofitting is done by adding low pressure (LP) ST and condenser to expand the steam that was supplied to the DP in the turbine to produce more work. In this paper, it is suggested that the CPDP widely used in the GCC to become a tri-generation plant producing EP, DW (by SWRO), and chilled water for district cooling (DC). An analysis is presented for the newly suggested configuration. It showed that a reference plant can be fitted with SWRO to replace the DP of MSF or ME-TVC and gives almost the same DW production capacity for the identical consumed EP by the MSF units. The process heat that was supplied to the thermal desalting units would be utilized for DC system using an absorption cooling unit(s). Comparisons of absorption cooling with the EP driven mechanical vapor compression refrigeration; and SWRO with the MSF desalting systems are illustrated in this article. The benefits of using DC in the GCC are also presented.

Keywords: Tri-generation power plant; Co-generation power plant; District cooling; Seawater reverse osmosis

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1. Introduction

In Qatar and all the Gulf Co-operation countries (GCC), summer cooling air-conditioning (A/C) is almost a necessity in all houses and public buildings. In these countries, the estimated electric power (EP) consumption is about 2/3 of the summer EP peak power production and about 50% of the consumed EP all year around. The summer in Qatar is very hot and humid with temperatures ranging from 30 to 50℃, with 40℃ average maximum temperature, and relative humidity range of 25–75%; see Fig. 1. The generated EP increased in Qatar from 13,232 GWh in 2004 to 28,144 GWh in 2010, that is, average annual increasing rate of 14% due to increasing of population and standard of living, and government highly subsidization (about 70%). The monthly generated EP was 1,436,158 MWh in February 2010 and was 3,321,230 MWh in August 2010, with the difference (1,885,072 MWh) is clearly accounted for A/C or 57% of the total EP generated in August. The maximum load in one day in summer of 2010 was 5,090 MW, and the minimum one-day load in winter of the same year was 1,570 MW as given in Fig. 2. This is due to the produced EP that follows the A/C demand (or cooling load or ambient temperature).

2. Consumed fuel due to desalted seawater production

Qatar's natural water resource is almost groundwater (GW) only. The GW replenishment rate per capita in cubic meters per year (m^3/y. Ca) is about 29 m^3/y Ca. The water poverty line is 1,000 m^3/y. Ca. The GW abstraction rate was 400 Mm^3/y in 2012, while replenishment rate is 58 Mm^3/y. Thus, GW is over-exploited, depleted, and quality deteriorated. Qatar depends on desalted seawater (DW) to satisfy almost all (99.9%) of its municipal water needs using thermal type desalting systems such as multistage flash (MSF) and multi-effect thermal vapor compression (ME-TVC) desalting plants (DP). The MSF and ME-TVC desalting systems are energy intensive processes that consume about 200 MJ of fuel energy for each produced one cubic meters of DW, or 200 MJ/m^3 when the DW is produced in co-generation power desalting plant (CPDP). In CPDP, steam is extracted from steam turbines (STs) and supplied to the DP. The extracted steam is at relatively low pressures (LPs) and temperature compared to the turbine throttling (inlet) conditions. This steam expands first in the turbine and produces work from the throttling conditions, say at 100–160 bar, and about 500℃, to the extraction (or discharging) point of the desalination plants at about 2–3 bar and 100–150℃. The specific consumed fuel energy can reach 360 MJ/m^3 when the DP is directly supplied with steam from steam generators; as in single-purpose DP, or in CPDP when STs are not operating and the steam supply comes directly from generators. In winter, large numbers of STs are put out of operation due to decreasing the EP load. Qatar's produced DW increased from 225.1 Million cubic meters yearly (Mm^3/y) in 2004 to 373.6 Mm^3/y in 2010, that is, 13.2% annual increasing rate. Based on current trends, DW consumption through 2020 is expected to increase 5.4% a year for Qatari's and 7% a year for expatriates [3]. In 2014, the expected DW annual product is 480 Mm^3/y, if 6.5% only annual increase is assumed as in 2010–2014. The estimated fuel energy when all desalination plants are supplied with steam extracted (or discharged from STs) is 96 M GJ for 2014 and 115.2 M. GJ if 25% of the DW is

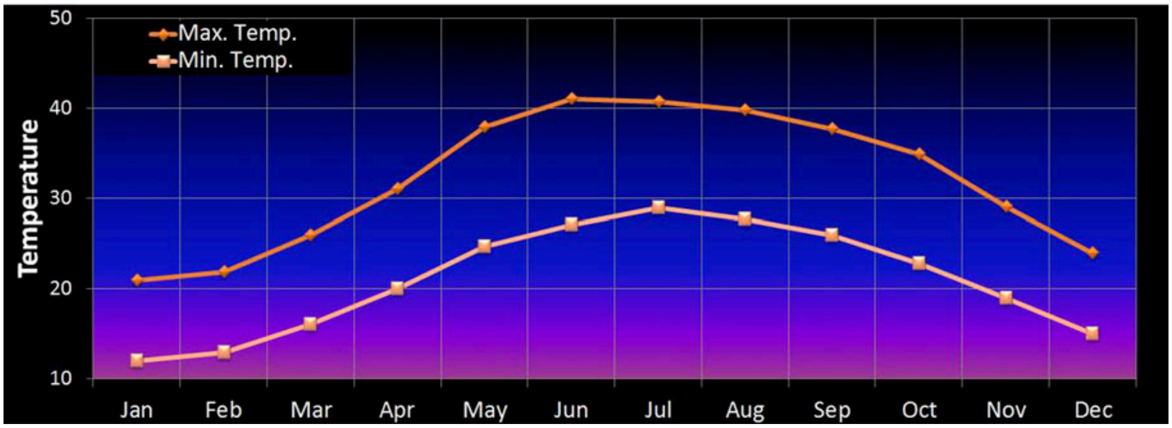

Fig. 1. Doha's average minimum and maximum temperature over the year [1].

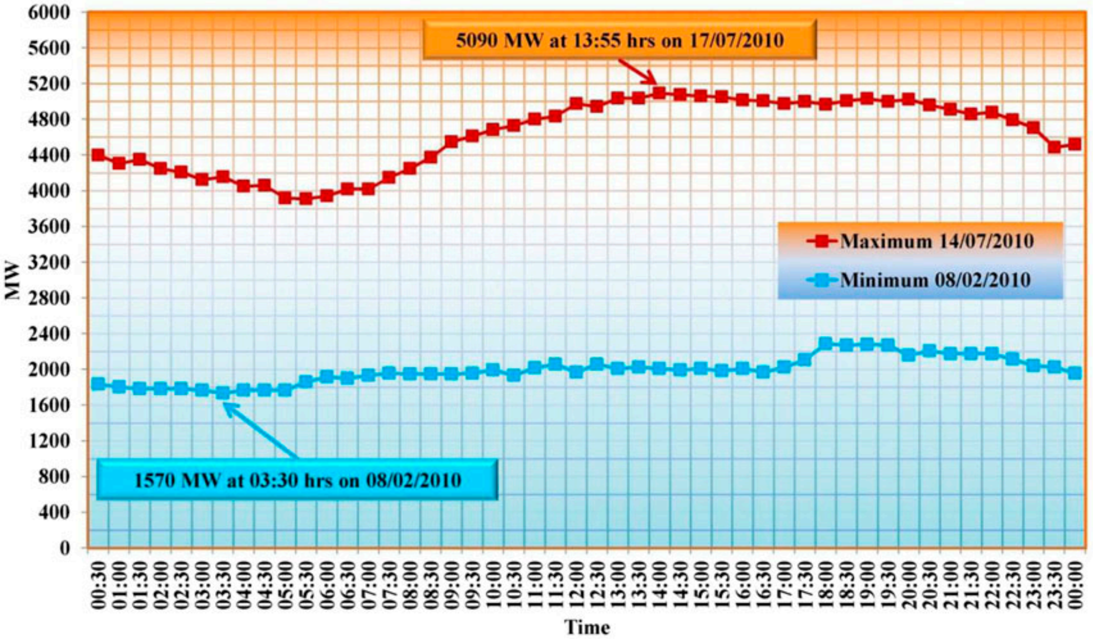

Fig. 2. Half hourly load curve for system maximum on 14/07/2010, and minimum 08/02/2010 [2].

produced by steam directly supplied from steam generators.

3. Reference CPDP

It is wasteful, from the thermodynamics viewpoint, to use fuel to generate the steam required by the MSF or ME-TVC thermal desalting systems, say at temperature of 110–120˚C and pressure of 2–3 bar. This steam has low availability compared to steam is generated in power plant (PP) at high pressures (HPs) (more than 100 bar) and temperatures (more than 500˚C) to produce EP in PP. Therefore, CPDPs are used to produce both EP and process heat for DPs. In these plants, steam is generated and fed to ST at HP and temperature. The steam expands in ST to produce work before its extraction (partially or totally) to the MSF or ME-TVC desalination units at a relatively LP (about 2–3 bar). Good percentage of fuel energy (up to 50%) can be saved using CPDP compared to operating the thermal DP directly with steam generated in a steam generator. This is illustrated using a Reference CPDP using gas turbine (GT) combined cycle (CC) and MSF desalting units. Schematic diagrams of the reference plant (called the Shuaiba plant) are given in Fig. 3(a), and 3(b).

The plant includes

- Three GT (made by GE Company and known as GE912FA) and are operated by natural gas (NG),
- Three Heat recovery steam generators (HRSG) operated by the exhausted hot gases from the GT,
- One back pressure steam turbine (BPST) operated by the steam generated in the three HRSG, and
- Three MSF desalting units supplied with the steam discharged from the BPST.

Many similar plants are operating in the GCC, e.g., Jabal Ali in the United Arab Emirates (UAE), and Ras Girtas, and Mesaieed plants in Qatar. The reference plant is designed with high temperature summer of condition of 50˚C, humidity ratio 30%, and atmospheric pressure of 1.013 bar to suit the GCC summer conditions. The GT's produce about 2/3 of the total EP of the CC plant. The temperature of the exhaust gases discharged from the GTs and supplied to three HRSG is around 625˚C. Each HRSG generates 1/3 of steam that operates ST. The BPST increases the plant EP output (about 1/3 of the total EP output). In ideal cases, the total enthalpy increase from the feed water inlet to the steam outlet in the HRSG is equal to the enthalpy loss by the exhaust gases. The CC plant has high overall thermal efficiency, and is supposed to use a cheap and clean NG. Each of the GT (GE912FA) produces 215.5 MW of EP, and the ST produces 215.7 MW of EP. The three HRSG produce 293.58 kg/s steam supplied to the ST. The CC plant nominal EP

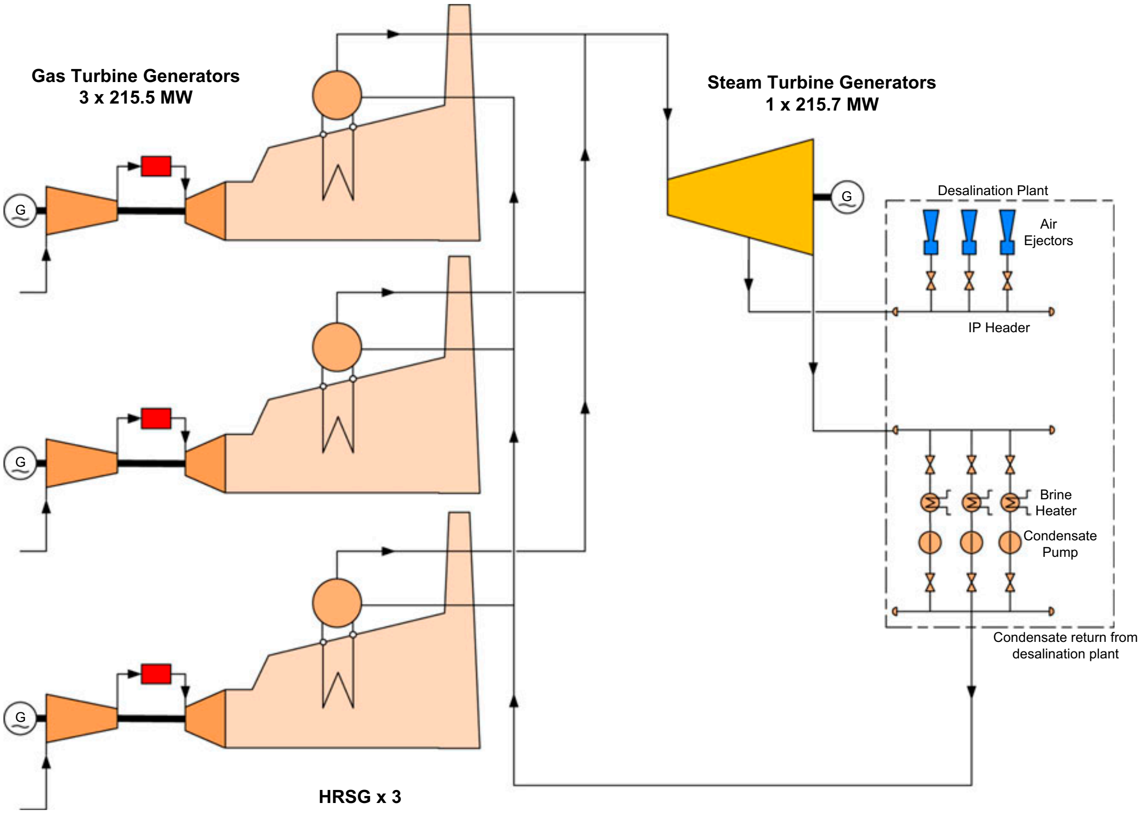

Fig. 3a. Schematic diagram of Shuaiba North gas/steam combined cycle (GTCC), reproduced from [4].

gross capacity is 862.2 MW; net capacity is 819.7 MW, and 45 MIGD (204,570 m^3/d) of DW.

Due to EP used for pumping in the three MSF units (34.1 MW), the net EP, after deducting pumping energy is 785.6 MW. Data of the reference plant are given in Table 1.

Note that the ST power output can be calculated as follows:

W_{ST} = (293.25 × 3,551–7.5 × 3,343–287.7 × 2,781.5)/1,000 = 215.7 MW, where 293.25 kg/s is the steam flow rate to the ST at an enthalpy equal 3,551 kJ/kg, and 7.5 kg/s is the steam extracted to feed water heater at enthalpy 3,343 kJ/s and 287.7 is the steam flow rate discharged to the 3 MSF units at 2781.5 kJ/kg enthalpy. Clearly, the efficiency of the plant ($W_{CC}/Q_{f,CC}$) is decreased from 49% when both EP and process heat to 46.7% when EP only is produced.

The real value of the steam used as thermal energy input to the MSF (or ME-TVC) units depends on how much work it can produce if expanded in a LP turbine from its turbine extraction (or discharge) state to the condenser conditions. This produced work is considered as work (or EP) loss that can be calculated and is equivalent to the thermal energy supplied to the MSF unit.

The case of the reference plant is considered here, see Fig. 3(a). The three MSF desalting units of 15 MIGD capacity each (or 2,368 kg/s total capacity for the three units). The steam leaves the turbine at the rate of 291.6 kg/s (1,049.88 ton/h), 2.8 bar pressure, 159.4°C temperature, and 2,782.8 kJ/kg of enthalpy. If this steam was expanded in LP turbine to a condenser at a pressure of 8 kPa, its enthalpy at the LP turbine exit would be 2,345.5 kJ/kg and the work output would be

$$\left\{\begin{matrix}\text{Work loss due to steam}\\ \text{discharged to three MSF units}\end{matrix}\right\} = 291.6 \times (2782.8 - 2345.5) = 127.5\ \text{MW}$$

Noncondensable gases have to be removed from the stages of the MSF units using steam ejectors operated with steam is extracted from the ST at a relatively HP than that supplied to the brine heater. The flow rate of the steam supplied to the ejectors of the three MSF units is 5.53 kg/s (19.9 ton/h); and at 30.1 bar pressure, 448.1°C temperature, and 3,342.5 kJ/kg of enthalpy. The expansion of this steam in a ST to the condensing pressure of 8 kPa, and 2,345.5 kJ/kg enthalpy would produce work at rate of:

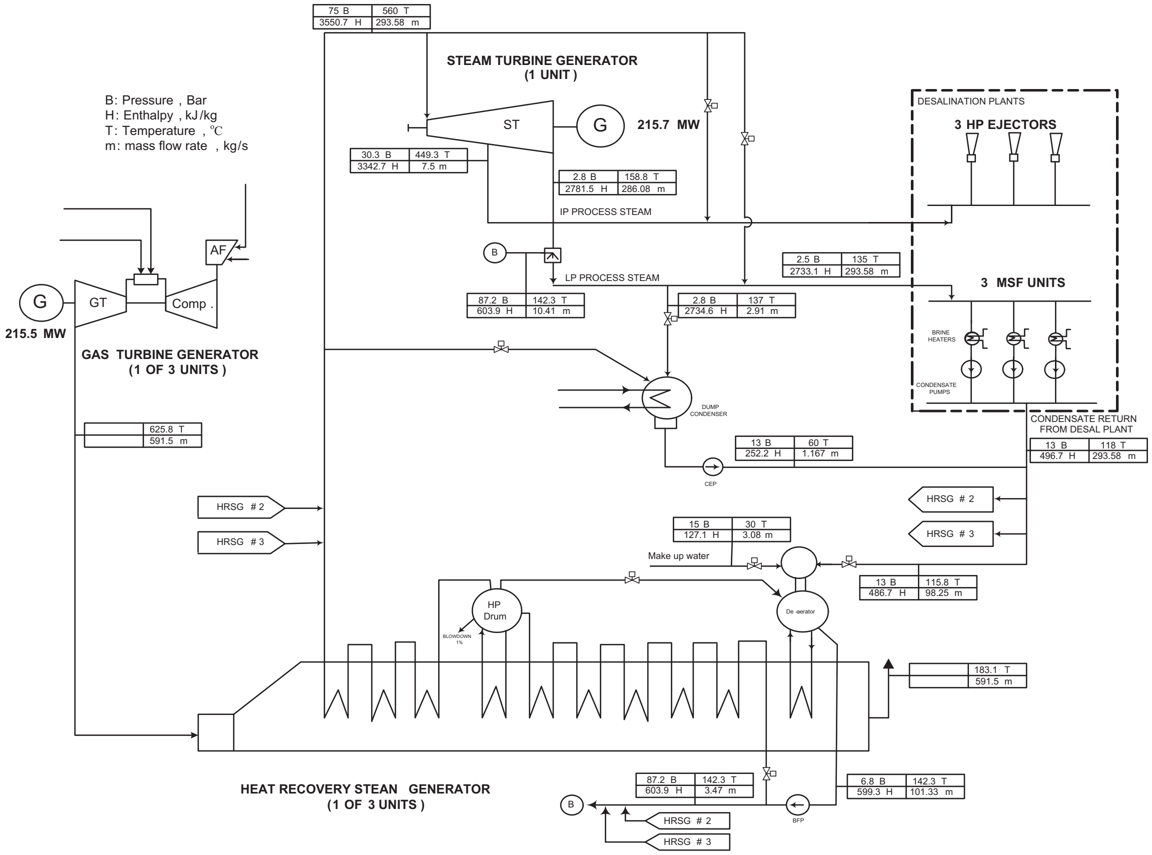

Fig. 3b. Flow sheet of Shuaiba North GTCC.

$$\left\{\begin{array}{c}\text{Work loss due to steam}\\ \text{extracted to three ejectors}\end{array}\right\} = 5.53 \times (3342.5 - 2345.5) = 5.5\ \text{MW}$$

Therefore, the work loss by the steam supplied to the 45 MIGD (2,368 kg/s) DP is 133.0 MW, or 56.17 kJ/kg (15.6 kWh/m^3). Adding 4 kWh/m^3 of pumping energy to the 15.6 kWh/m^3 gives the specific equivalent mechanical energy (SEE) counting for pumping and thermal energy is equal to ≅20 kWh/m^3. The corresponding consumed specific fuel energy is 200 MJ/m^3 when this mechanical energy is produced in a PP of 36% overall efficiency. These numbers are to be compared with SEE = 36.6 kWh/m^3, and specific fuel energy = 366 MJ/m^3 calculated before if the steam is directly supplied to the DP from fuel fired boiler.

Table 1
Technical specifications of Shuaiba North GTCC power-desalination plant

GT	GE912FA
Number of units	3
Type of fuel	NG
LHV, kJ/kg	47,806
Gross output, MW	215.5
Fuel flow rate, kg/s	12.897
Air flow rate, kg/s	578.62
Exhaust gas temperature, ℃	625.8

Although the use of CPDP has reduced the SEE from 36.6 to 20 kWh/m^3 (or 45.3% saving), it is still much higher than that of seawater reverse osmosis (SWRO) desalting system. The SWRO consumes about 4–5 kWh/m^3 desalting seawater of high salinity (42–45 g/l) similar to that in the Gulf area. To generate the specific pumping (or electrical) energy of 5 kWh/m^3 used by SWRO, by a PP having 36% overall efficiency, the specific consumed fuel is 50 MJ/m^3. This 50 MJ/m^3 is compared to 200 MJ/m^3 consumed by thermal desalination system (e.g., MSF or ME-TVC) in CPDP, and 360 MJ/m^3 for direct steam supply from steam generator. This is the reason that MSF and ME-TVC should be replaced by the SWRO in all future plants. The widespread use of the MSF in the GCC is due to the low fuel prices used in calculating the EP and DW

Table 2
Simple calculation analysis for Shuaiba North GTCC power-desalination plant

Power output by three GT	= 3 × 215.5 = 646.5 MW
Fuel heat added to three GT, Q_f	= 3 × 12.897 × 47.806 = 1847.1 MW
GT efficiency, η_{gt}	= 646.5/1847.1 = 35.0%
Exhaust gases from each GT, m_g	= 12.897 (fuel) + 578.62 (air) = 591.52 kg/s
Heat supplied to each HRSG, Q_{HRSG}	= $m_g \times C_p \times (T_4—T_{stack})$ = 591.52 × 1.11 × (625.8–183)/1,000 = 290.74 MW
Generated steam mass flow, m_{steam}	= $Q_{HRSG}/(h_{S\_}h_f)$ = 290,740/(3550.7-559.3) = 97.2 kg/s
Heat supplied to steam cycle, Q_{steam}	= 3 × 290.74 = 872.22 MW
ST power output	= 215.7 MW
ST efficiency, η_{st}	= 215.7002F872.22 = 24.73%
Heat supply to each MSF unit Q_{des}	= 97.75 (2733.1-496)/1,000 = 218.68 MW
Specific thermal energy in MSF q_{des}	= Q_{des}/D = (218.68/789) 1,000 = 277 MJ/m^3
Work loss due to steam supply to DP	= 42.57 MW for one MSF = 133.33 MW for three MSF
CC plant efficiency with DP = W/Q_f	= W/Q_f = [(3 × 215.5) + 215.7]/1,847 = 0.466811
CC efficiency w/o DP	= $(W + W_{des})/Q_f$ = [(3 × 215.5) + 215.7 + 42.57]/1847 = 49%
W_{des}	= $m_s \times (h_{MSF\_}h_{con})$ = 42.57 MW/MSF
$W_{ejector}$	= 2.5 MW
W_{des}(total)/MSF	= 45.07 MW
W_{des}/D	= 57.12294 (15.87 kWh/m^3)
Pumping energy/MSF units	= 14.4 × 789/1,000 = 11.36 MW

production costs, compared to the international fuel price.

If the MSF (or ME-TVC) desalination plant is abandoned, another substitute to utilize the process heat supplied for desalting plant should be provided. Otherwise, the plant will be operated as a single-purpose PP, and the process heat will be dumped to the environment unless major retrofitting is done to the plant by adding LP steam turbine and condenser. This is to avoid the significant decrease of the plant efficiency if the process heat is dumped to the environment.

4. Suggested tri-generation plant

Efficient operation of the existing CPDP requires that both EP and process heat production have to continue. The process heat (in the form of steam at 100–130˚C) can be utilized for driving absorption water chillers (ABC) for district cooling (DC). The ABC are operated by thermal energy at conditions similar to that used for MSF units. DC is very much needed in Gulf area. The conditions of steam (or hot water) supply to Water–lithium bromide chillers are similar to the conditions required by the MSF (or ME-TVC). Meanwhile, the same Ì plant would produce DW at almost the same capacity, but using SWRO plant that replaces the MSF (or ME-TVC) plant. This plant would be tri-generation plant that generates simultaneously EP, DW, and DC from the same amount of combusted fuel. The use of tri-generation plant results in better utilization of fuel energy as well as the available CC equipment. The benefits of retrofitting the CPDP to become Tri-generation plant is demonstrated on real operating CC plant in the GCC. Fig. 4 illustrates the suggested tri-generation plant, which comprises power generation, desalting water production, and chilled water for DC. The idea of tri-generation (sometimes called poly-generation) to produce DW, chilled water for DC, beside the main objective of producing EP in one plant is suggested and studied by many researchers, e.g., following references [5–10]. The main objective is to improve the performance of the desalination system. However, fewer researches are aimed to co-production of desalinated water and cooling effect. Alarcón-Padilla et al. [11,12] evaluate the connection of a double effect absorption heat pump driven by a fire-tube gas boiler, to 14 effects MED unit. The hot cooling water from the absorption cycle condenser is used to drive the MED unit. The lower effects are cooled by the cold water produced in the absorption cycle evaporator. They used two water tanks for steady state operation of the unit. No cooling effect was used in this cycle. Wang and Lior, [6,13,14], proposed and mathematically analyzed a process of absorption cycle for space cooling combined with a multiple-effect evaporation system for desalination. In their study, the condenser of the absorption cycle is replaced by a low temperature multi-effect evaporation system driven by steam generated in the generator. The system is driven by steam generated externally. The combined system gives a 60

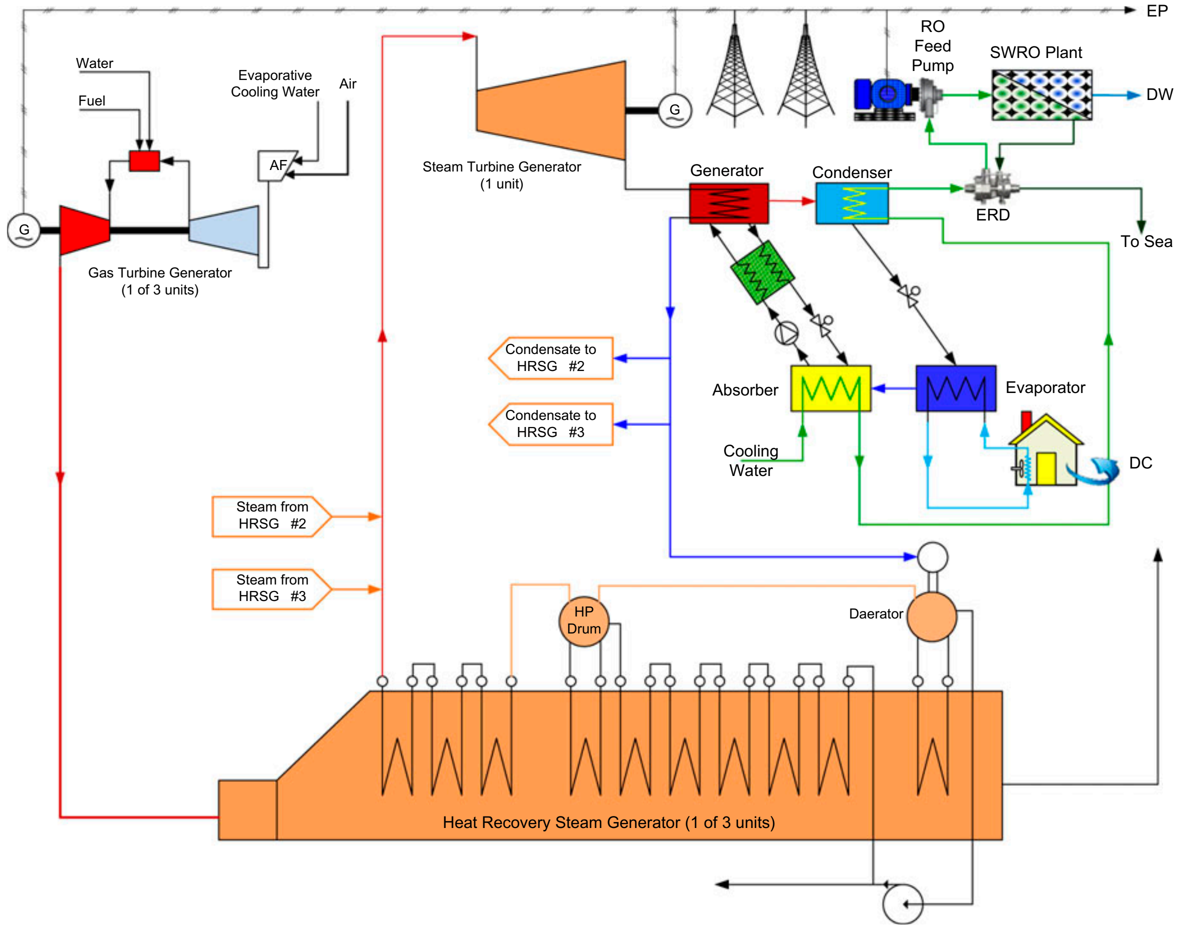

Fig. 4. A schematic diagram for the suggested tri-generation plant.

to 78% water production gain over stand-alone Low temperature Multi-effect evaporation (LT-MEE) unit run by the same heat source conditions.

5. Replacement of the MSF with SWRO plant

The energy inefficient MSF (or ME-TVC) seawater desalting method should be replaced by the more energy-efficient SWRO desalting system. The delay of using the SWRO for desalting seawater in the GCC is due to the complex feed water pretreatment required to deal with bio-fouling and the underestimation of the fuel cost. Proper SWRO feed water pretreatment is one of the main factors that affect the reliability of the SWRO desalting system. Other factors are algal blooms, lack of experience with high total dissolved solids (TDS) water in SWRO plants, high-temperature waters, and the old views about the lack of durable membranes for the RO process in high salinity water are also factors causing the application of the SWRO system [15].

Kuwait's first large commercial SWRO desalination plant in Shuwaikh started its operation in 2010. This plant has a capacity of 136,260 m^3/d (30 MIGD) and is reported to be running well. The plant's design gave special attention to the feed seawater (SW) pretreatment as the SW in the area is highly saline, rich in organic components, and known for occasional red tides, which can last for 10 d. The SW pretreatment consists of dissolved air flotation (DAF), Fig. 5, and ultra-filtration (UF) membrane modules.

Both DAF and UF remove efficiently high concentrations of suspended solids and small-sized colloidal particulates. The produced RO feed water has a consistent silt density index value of less than 3.0 all times with original turbidity level up to 31 at Shuwaikh. Therefore, this state of art pretreatment is functioning adequately with the worst SW in Kuwait, even during a red tide event in 2012. The same UF system has been selected for use in the UAE Al-Zawrah SWRO plant being built in Ajman, and DAF and UF were

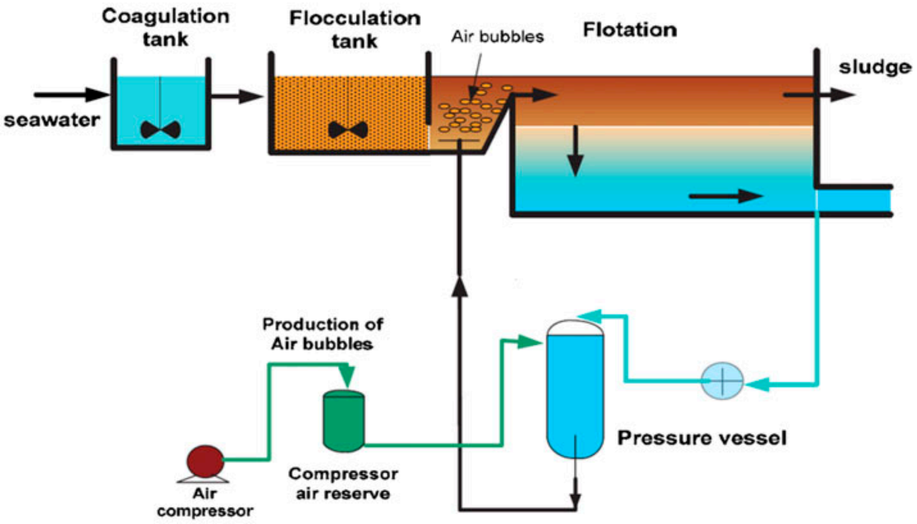

Fig. 5. A sketch of a typical DAF unit.

built in Al Hamriya in Al-Sharja, UAE. The Shuwaikh SWRO plant uses modern energy recovery devices (ERD), 187 PX-260 pressure exchangers supplied by Energy Recovery Incorporation, to minimize energy consumption, and they save 12.7 MW of power in total.

Another large CPDP, Al-Dur plant that produces 218,200 m^3/d of DW and 1,234 MWe of EP have been built by GDF Suez, and began full commercial operation in February 2012. It is too soon to know whether the operations will go smoothly, but the purchase agreement specifies that the Bahrain water authority will purchase electricity and water at fixed tariff rates of 14 fils per kWh, and 350 fils per cubic meter of water (close to \$1/m^3) until mid-2033.

The trend of using SWRO in the GCC is motivated by its low consumed energy compared to other thermal desalting methods. Fig. 6 shows the specific consumed energy of the MSF, ME-TVC, and SWRO. Fig. 7(a) and 7(b) shows collection of DW cost data produced by MSF and SWRO in the GCC. The SWRO water production cost is steady at about \$1/m^3. The MSF shows more variation, much of which can be explained through energy cost accounting methods. When energy is considered at market oil prices, MSF is much more expensive than SWRO, but in Qatar and Kuwait, the cost of water produced using MSF is sometimes calculated using NG or oil priced either at extraction cost, or at highly subsidized cost, or at no cost at all.

Moreover, the operation of MSF (or ME-TVC) is directly related to the steam turbines operation to supply steam to the DP. In winter, when the EP load factor is low, as shown in Fig. 2, many of the steam turbines are stopped. This requires increasing the capacity of the MSF (or ME-TVC) units that operate when steam turbines operating. The increased output of DW satisfies the spontaneous need plus storing capacity that can be used when the some of the steam turbines (and thus some MSF are not operating). When the MSF unit is replaced by SWRO, and during the EP demand falls in winter, the surplus EP can be utilized to produce DW by the SWRO units.

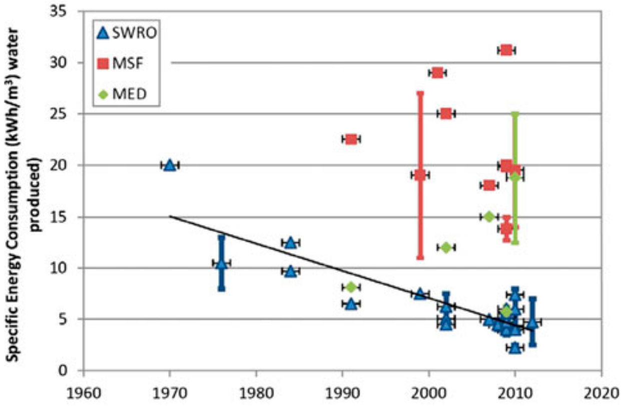

Fig. 6. Specific energy consumption of desalination technologies [15].

6. Suggested SWRO plant design

The suggested SWRO takes the advantages of best known pretreatment, ERD, and material choices to

Fig. 7a. Cost of water production with MSF and SWRO in Arabian Gulf waters, 2007–2012 [15].

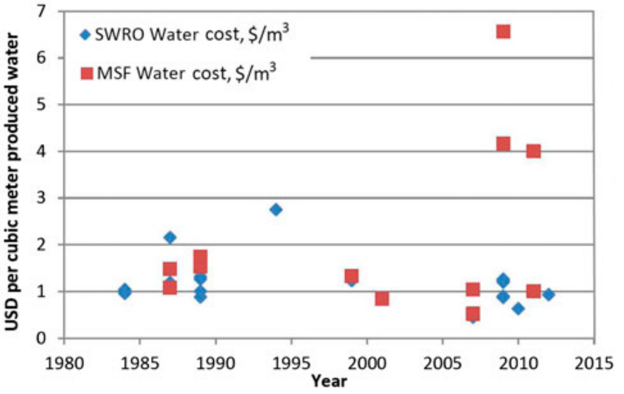

Fig. 7b. Cost of water production with MSF and SWRO in high TDS waters, 1984–2012 [15].

insure the plant reliability and highest load factor. Similar approach is used with the choice of Al Hamriya SWRO plant in Sharjah, UAE that has flow diagram shown in Fig. 8. The plant should use the same open seawater intake of the reference Shuaiba plant (common intake for power station cooling water), coarse screens and band screens, and pretreatment using DAF and UF. The SWRO block would be single pass/single stage designed for high Boron removal. The SWRO plant capacity can be less than the 45 MIGD of the reference MSF plant, since the SWRO operation can be operated with no interruption, while the MSF plant was directly related with the operation of ST, which can be stopped during winter. Therefore, the suggested SWRO plant capacity is 40 MIGD to give the cumulative output of the MSF over time. The reasonable SWRO train capacity is 2.5 MIGD (11,365 m/d), similar to Al Hamariya plant and thus 16 trains are required. The SWRO plant design parameters are SW salinity, (TDS) = 42 g/l, temperature 28 ℃, 182,000 m^3/d, permeate TDS = 450 mg/l, and maximum permeate boron concentration <1 mg/l.

Examples of membrane type used are the spiral wound membranes like Hydranautics SWC5 used in Al Hamariya plant in Sharja, UAE, and SWC3+ used in New Quidfa SWRO plant in UAE; or the hollow fiber membrane type Toyobo Hollosep used in the 2005 rehabilitated Addur plant in Bahrain. If the Hydranautics SWC5 is chosen, it has productivity of 34.2 m/d (9,000 GPD) at standard test conditions and salt rejection of 99.8%. The SWCS have very good Boron rejection that can give boron concentration less than 1 mg/l in the product of single stage [16].

The average flux of the SWC5 is 16.6 liters per m^2 per hour (lmh) if the feed water has good quality. Therefore, if the SWC5 has 35-m^2 area, the number of membrane modules would be $N_{membrane} = \frac{2.5\times 4{,}546\times 1{,}000/24}{16.6\times 35} = 815$. If seven elements are inserted in each pressure vessel (PV), then the number of PV is 116. The EP used to drive the SWRO can be estimated first by calculating the energy used by the HP feed water pumps to the membranes, then estimate the auxiliary power required for the rest of the plant. For a recovery ratio of 1/3, the feed flow rate to produce 40 MIGD (2,104.63 kg/s) is 6,313.89 kg/s or 6.314 m^3/s. For 65 bar pumping pressure, EP consumed by the HP pumps is 6.314 × 6,500/0.8 = 51300.35 kW. The brine flow rate is 4.21 m^3/s, say at 62 bar, can be supplied to pressure exchanger of 0.92 efficiency to recover 24,009.62 kW, and the net consumed EP is 27,291 kW. If this energy represents 80% of the total consumed energy of the plant, the EP consumed by the SWRO plant is 34,113 kW. The pumping energy supplied to the 3 MSF units of 45 MIGD (2,367.708 kg/s) capacity in the reference plant (4 kWh/m^3) is 34,095 MW. This is almost the same as the EP consumed by the new suggested SWRO plant. So, replacement of the MSF units of 45 MIGD by the SWRO units of 40 MIGD does not need any additional EP than that consumed by the MSF units; while leaving the process heat (Q_P) of 656 MW to be utilized for other purposes.

7. Better application for process heat

Most PPs in Qatar and other GCC are designed as CPDP to produce both EP and process heat (Q_P) for DPs. If the SWRO desalting system replaces the MSF (or the ME-TVC) system, the Q_P from the CPDP would not be needed, unless it is used in other applications. If Q_P is not used, the CC plant would produce only EP, but after retrofitting to operate as a

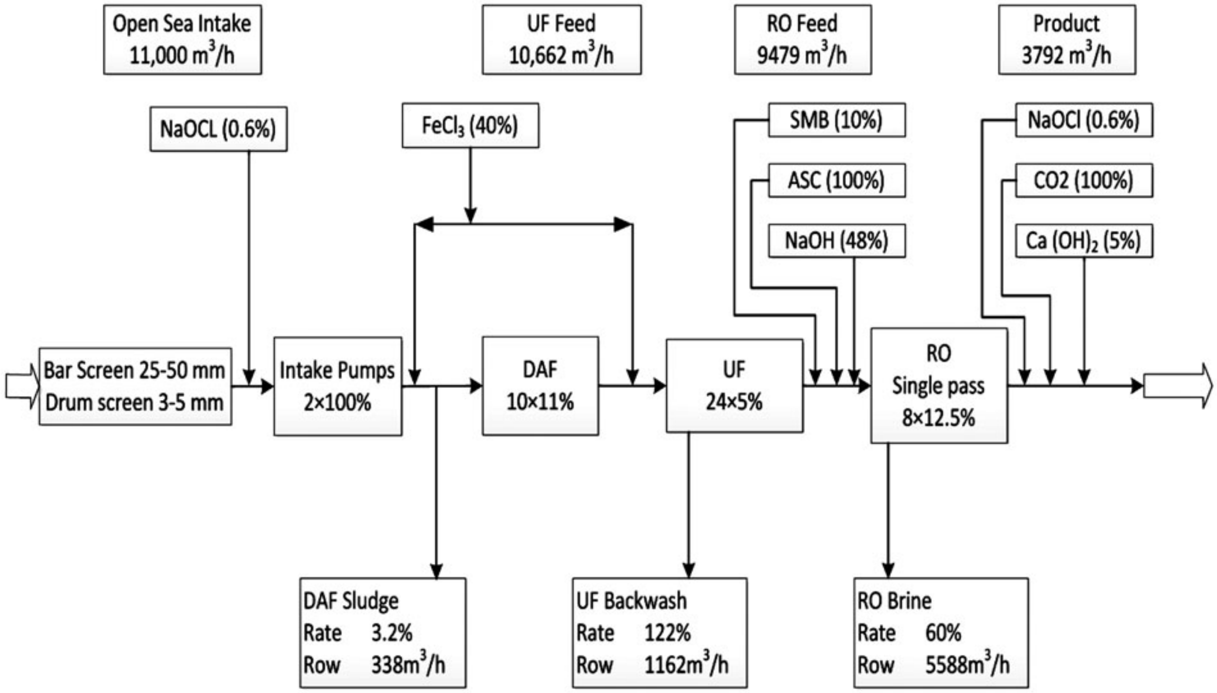

Fig. 8. HAMPS RO plant phase II process block diagram, source [16].

single-purpose PP. This retrofitting can be done by adding LP steam turbine to utilize the steam that was discharged to the MSF unit by its expansion to atmospheric condenser conditions to produce more work. This also necessitates adding new condenser. Otherwise, Q_p would be dumped into the sea and the CC overall efficiency is significantly decreased. Simple analysis of this plant is given in Table 2.

If this Q_p is to be utilized to save the very expensive cost of retrofitting of the plant, it is suggested here to supply the Q_P to H_2O–LiBr absorption (ABS) chillers to generate chilled water for DC needed in Qatar. The reference CPDP would work efficiently if productions of both EP and Q_P continue. The ABS of water-lithium bromide (H_2O–LiBr) type can be driven by steam or hot water of the same temperature range used in the MSF (or ME-TVC) desalting units. The absorption H_2O–LiBr water chillers have a low coefficient of performance (COP), about 0.7. The COP represents the cooling capacity divided by the energy supply. This is lower than the COP of the presently used mechanical vapor compression (MVC) refrigeration system operated by the EP, about 3.5. By direct comparison of COP in both cases, many think the ABS is less efficient than the MVC system. This is not right in all cases, as the energy input in the ABS is thermal energy is low quality, the energy supplied in the MVC is high-quality mechanical energy as shown later.

The use of the reference plant to produce EP and chilled water for summer A/C, besides replacing the MSF units by SWRO units results in better utilization of fuel energy. It leads also to better usage of the available equipment. The benefits of using this approach as compared to the use of the EP driven mechanical vapor refrigeration MVC machines and producing power to drive them are illustrated here.

The ABS machines, when located in the CC plant, can supply chilled water to air-handling units located in buildings to be air-conditioned. Hot water can also be supplied to the air-handling units when heat is required in winter. In case of dismantling an MSF desalting unit, its brine heater can serve as a heat exchanger to produce hot water from the extracted steam.

8. District cooling

DC, network-based centralized cooling system, has not been deployed efficiently in the GCC. DC makes economic sense in areas of high cooling density. At present, DC is one of three main systems used for A/C in GCC. These include window units (or split) systems that provides A/C to single room, apartment unit, or small building. Large buildings use central air or water-cooled chillers, which are placed on a building's roof or in the basement. The least localized system is DC, in which is a central plant that supplies chilled water through piping network to multiple buildings within a local area, see Fig. 9.

In DC, chilled water is circulated from the central plant to buildings, with a small amount of consumed water because of closed-loop operation. By offsetting network costs, DC offers three main benefits: low energy requirement, more efficient capacity use, and peak-period saving potential. These benefits are outlined in Ref. [17] as follows:

(1) DC typically consumes 40–50 percent less energy for every refrigeration ton hour than conventional in-building technologies, due to the use of more efficient chiller technology applied in DC. The DC's plant can maintain a steady level of efficiency over time because of their specialized operations and maintenance.

(2) DC typically needs around 15% fewer capacities for the same cooling loads than distributed cooling systems at the unit level. Unlike conventional A/C, DC is more efficient in capacity deployment: load diversity and flexibility in capacity design and installation. The DC system tends to serve diverse loads such as residences, offices, and commercial establishments that do not require simultaneous cooling.

(3) DC offers a thermal storage capability that can smooth out power requirements over the course of a day, thereby reducing the strain on the power system at peak hours. It can store up to 30% of potential output by holding chilled water in tanks. By contrast, in-building systems impose their full load on power systems at peak times.

(4) DC offers a more reliable service because of ongoing professional operation and maintenance and is quieter than conventional cooling.

Therefore, the reference plant can be used to produce EP and chilled water for summer A/C, besides replacing the MSF units by SWRO units. These resulted in a better utilization of fuel energy, besides the best usage of the available equipment. The benefits of utilizing this approach, compared to the use of conventional EP driven mechanical vapor refrigeration MVC machines, and producing power to drive them are illustrated here.

9. Comparison between MVC and ABS for DC

The main difference between EP driven MVC and the thermally operated ABC systems is the method used to raise the LP vapor generated in the evaporator due to absorbing the refrigeration load to the condenser at HP, and returns it to the evaporator through throttling device. In MVC, mechanical compressor is used to deliver the LP vapor to the condenser at HP. In ABS, the LP vapor leaving the evaporator is absorbed first by strong Li–Br solution, and the resulted weak solution (liquid) is pumped with small pump and low mechanical energy to a generator. The generator is supplied with heat (the main energy input) to evaporate the vapor needed for the evaporator out of the solution, see Fig. 10(a) and (b).

An example of ABS refrigeration machine is the H_2O–LiBr machine producing chilled water at 6.7°C shown in Fig. 11. For the ABS system shown in

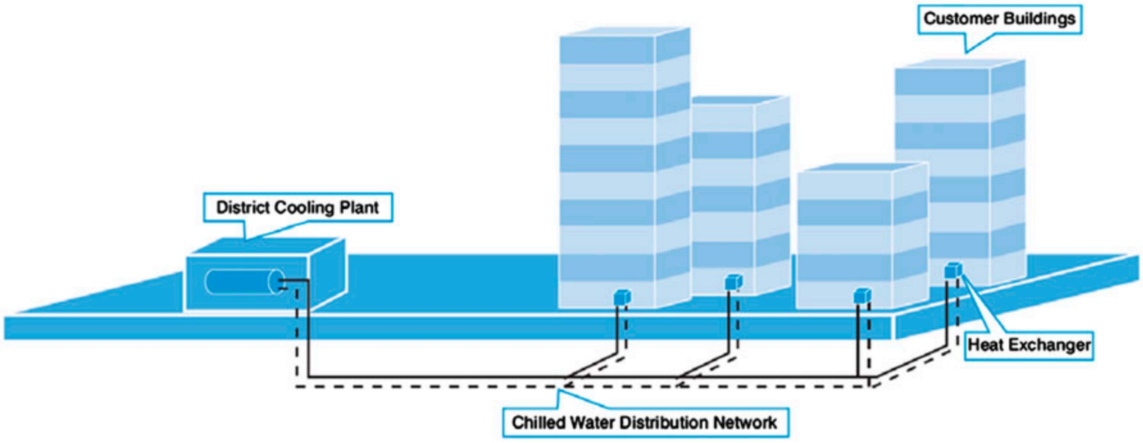

Fig. 9. Illustration of DC arrangement.

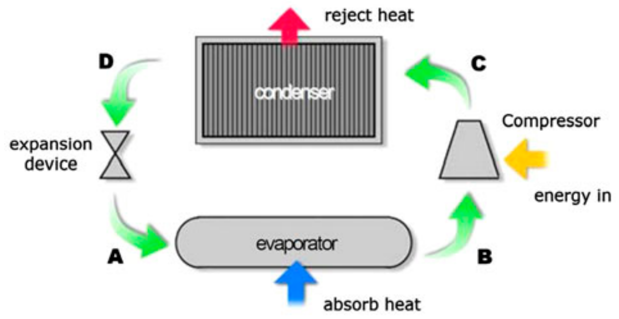

Fig. 10a. Components of MVC refrigeration cycle, trane absorber water chillers [18].

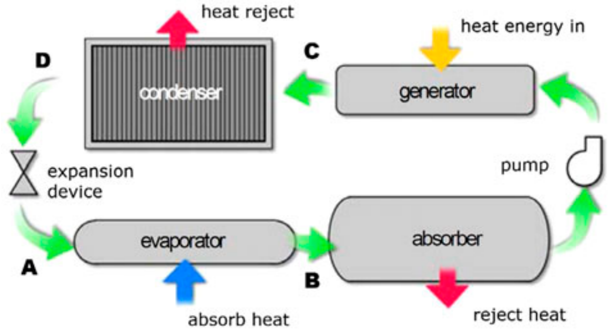

Fig. 10b. Components of absorption refrigeration cycle, trane absorber water chillers [18].

Fig. 11, about 0.7 gm of steam per second (g/s) is consumed per kW refrigeration at full load or 1.54 kJ of heat/kJ of refrigeration. This gives coefficient of performance, COP, (refrigeration energy/supplied energy) around 0.7. Although the COP of the ABS is about 1/5 times that of the MVC, this does not mean that MVC machines are five times more efficient than the TVC machines. The reasons are outlined for the reference plant is given here by an example.

Thermal energy supplied to the steam cycle is 866.46 MW to produce 215.7 MW of EP and to supply process heat to the DP of 3 × 218.68 = 656 MW of thermal energy. If the steam discharged to the DP was expanded in LP turbine, it would produce 133.1 MW as

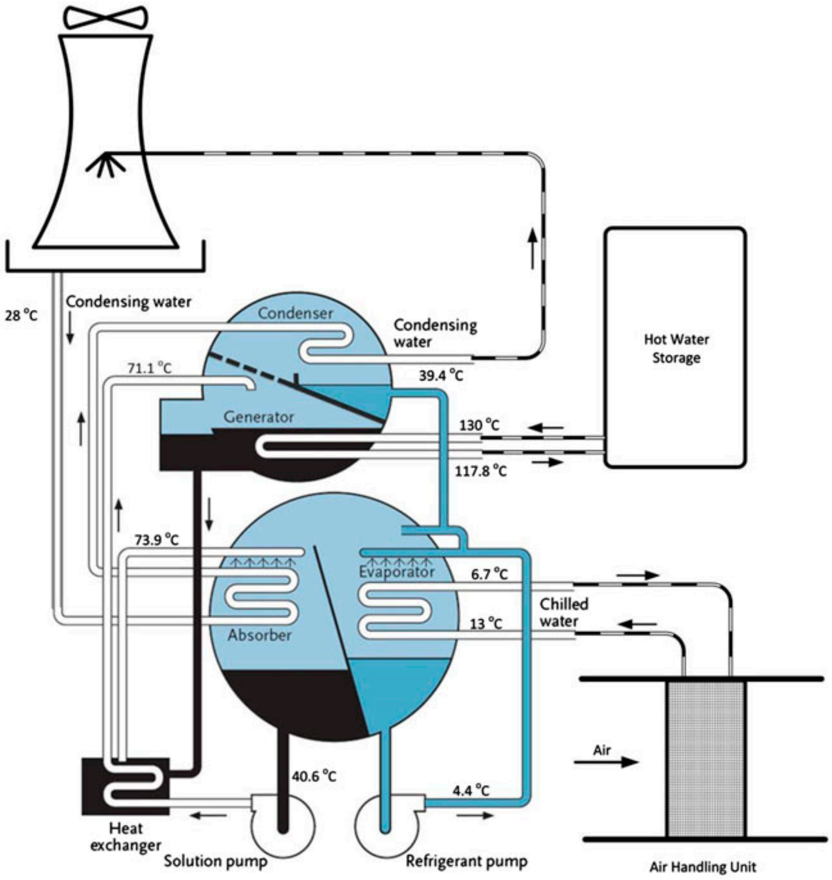

Fig. 11. Flow sheet of water–lithium bromide refrigeration machine producing chilled water for A/C, reproduced from [19].

shown before. Therefore, the 133.1 MW mechanical work is equivalent to the 656 MW thermal energy (Q_P).

The refrigeration capacity produced by 656 MW process heat using ABS refrigeration cycle, $Q_R = 656 \times 0.7$ (typical COP) = 459 MW refrigeration. The equivalent mechanical energy of 133.1 MW using MVC of 3.5 COP, would produce 465.85 MW refrigeration. This shows that when the Q_p was used to operate the ABS, it produces almost the same refrigeration effect of its equivalent energy when it operates MVC system.

Moreover, the ABS system is preferred, sometimes, over the MVC if unused boiler is available during summer months; when cheap heat energy source exists; and when 100% standby electric generator is required to operate the MVC system. Proven types ABS water chillers are commercially available in different capacity ranges, e.g., Carrier Company produces machines in the range of 70–815 ton refrigeration, and the York Company produces machines in the range of 114–1,378 ton refrigeration. Both products use water-cooled condensers and absorbers.

9.1. Thermal storage system

The EP demand follows the A/C cooling load, and the maximum load lasts for only few hours in hot summer days. Therefore, the installed capacities of both PPs and A/C systems are much higher than average demands.

The use of chilled water storage decreases the capacity of refrigeration machine to match the average load and allows continuous operation of these machines at full load. Uninterrupted operation of cooling machines at full load gives a better performance ratio, especially at night with low condensing temperatures.

10. Conclusion

Details of reference CPDP producing both EP and DW are illustrated; it is consisting of CC and MSF desalting units. This plant saves about 44% of fuel energy consumed by the MSF units when two separate plants, one for EP and one for DW are used. However, the energy consumed by the MSF is still about four times higher than the energy consumed by the SWRO desalting system. For this reason, MSF (or ME-TVC) is losing ground to the SWRO system worldwide. A retrofitting plan to replace the MSF with the SWRO is presented, and to direct the Q_P that was supplied to the abandoned MSF unit to absorption water chiller forming DC. The adoption of DC in Qatar would utilize the existing process heat from CPDP, lower the energy consumed by A/C machines, and flatten the EP demands in summer. In the retrofitted CPDP, the MSF pumping energy that was supplied to three MSF × 15 MIGD is almost enough to run the SWRO plant of 40 MIGD. The Q_P that was supplied to three MSF units is supplied to ABS water chillers to produce 459 MW cooling capacity. This would slow the ever-increasing demand for additional PP capacity due to the increase of A/C load. The 459 MW cooling load needs EP capacity increase by at least 114.8 MW when conventional A/C is used and about 100 MW when DC is used. The suggested plant consumes the original fuel input, while producing the same EP, needed DW, and 459 MW cooling capacity, and addition of PP capacity of 115 MW, that cost at least $M172.2, if the CC PP installment cost is $1,500/kW.

The use of chilled water storage would shave the power peak (the real cause of a low capacity factor) and ensure the operation of the refrigeration machines at a high-performance ratio, especially when they operate at low condensing temperatures at night. The ABC are well proven commercial products available in the market.

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