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## Towards sustainable seawater desalting in the Gulf area

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### Abstract

Gulf countries experienced rapid growth in the last four decades from oil production and its price increase. Natural water resources are very limited to meet this growth, and as result, desalted seawater in Kuwait became the main source of potable water, about 93% in 2002. The electric power and desalted water, produced in co-generation power desalting plants (CPDP), consumptions are continuously increasing, almost doubled every 10 years, due to population and standard of living increases. This led to the consumption of huge amounts of fuel, draining the country main fuel (and income) resource, and negatively affecting the environment. One tenth of Kuwait's oil production was consumed by the CPDP in 2003. If the trend of almost doubling the consumption every 10 years prevails, the total oil production may not be sufficient to desalt seawater for people to drink, and to produce power to run space air conditioning units (a necessity for Kuwaiti harsh weather). It is essential therefore to look for energy efficient ways to produce power and desalted water so as to save the nation's income of these non-renewable fuel resources, to save the environment and indeed life itself in Kuwait, and this is the objective of this paper. It reviews the presently used desalting methods and their energy demand, and the correctness of fuel allocation formulas for CPDP, to determine the most efficient methods to apply and the less efficient ones to avoid. Fourteen desalting cases are analyzed by using the current practice, with and without combination with power generation plants (using steam or gas or combined gas/steam turbines cycles). The specific fuel energy consumed and the emitted CO<sub>2</sub>, SO<sub>x</sub>, and NO<sub>x</sub> per m<sup>3</sup> desalted water were calculated for each case. The results show that operating thermally driven desalting systems by steam directly supplied from fuel-fired boilers is the most inefficient practice, and should be avoided. The use of the gas/steam turbine combined cycle, which is also the most efficient power-generation cycle, to drive seawater reverse osmosis (SWRO) desalination plants is the most efficient combination. Also, all conservation measures in utilization of both water and power should be applied. Reclamation of waste water, at least for non-potable water needs must be promoted, because it consumes less energy and at cost much lower than those of desalting seawater.

**Keywords:** Water desalination; Steam turbine power plants; Gas turbines power plants; Combined gas/steam power cycles; Dual purpose desalination plants; Energy consumption for water desalination; Sustainability; Air pollution; CO<sub>2</sub> emissions

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## 1. Introduction

Kuwait, like other Gulf countries, experienced very rapid growth in electric power and desalted water production in the last four decades due to the evolution of oil production and its price increase. One may ask, is this growth sustainable? The most used definition for sustainability [1] is the growth that meets the present generation needs without compromising future generations' ability to meet their own needs. Daly [2] stated that sustainability requires:

1. The use rate of renewable resources (e.g. groundwater) does not exceed the rate of their regeneration.
2. The use rate of non-renewable resources (e.g. fossil fuel, mineral ores) does not exceed the development rate of sustainable substitutes.
3. The pollutants emission rate does not to exceed the capacity of the environment to absorb and render them harmless.

While most of the data used in this paper pertain to Kuwait, the general situation and trends of water and energy use and of their impact on resources and the environment are very similar in most of the Gulf countries. The renewable annual water resource (ground water) in Kuwait is less than  $100 \text{ m}^3/\text{capita}^*$  (noting that annual  $1000 \text{ m}^3/\text{capita}$  marks the water poverty line!), while the extraction (consumption) rate is more than  $500 \text{ m}^3/\text{capita}/\text{y}$  [5]. Over-extraction depletes the ground water and deteriorates its quality. While Kuwait has large amounts of fossil fuel oil, which can be used for producing new water, that resource has other major uses and is finite, with no practical alternative for its substitution.

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\* Water replenishment in Kuwait comes from rain to the Dammam limestone aquifers in the Um Ghadir field along the border of Saudi Arabia, and a very small percentage of the precipitation infiltrates into the groundwater in Kuwait [3,4]. The estimated renewable water is  $75 \text{ m}^3/(\text{capita}\cdot\text{y})$  [5], but the current extraction is about  $510 \text{ m}^3/(\text{capita}\cdot\text{y})$ .

Although full sustainability may not seem possible for the time being, efficient power and water production, alongside with much more modest consumption, are essential to allow the present resources to maintain the country's development over a longer time period, i.e., to make it more sustainable.

In Kuwait, about 93% of potable water need was secured by desalting seawater in 2002 [6]. Table 1 gives the installed capacity of desalting units and desalted water consumption in the last four decades. The daily-consumed fresh water in l/capita increased from 137 in 1973 to almost 500 in 2003, and the population increased from 900,000 in 1983 to 2,540,000 in 2003, resulting in a 10-fold water consumption increase in Kuwait during that 30-year period. This necessitated the production of large amounts of desalted seawater with respectively large fuel consumption for it.

The annual population growth, including both Kuwaiti and non-Kuwait residents, is estimated at 3.8%, which more than double of the world average. Since water consumption obviously would increase with the population, it is noteworthy that in 1994 about 63% of the total populations were estimated to be non-Kuwaiti residents, pointing out that importation of foreign labor has an important effect on increasing the national water consumption.

Thermally operated desalting units usually obtain their heat input as steam supply; either extracted from steam turbines or from gas turbine exhaust heat recovery steam generators (HRSG) in combined cycle power generation systems (CC). Thus, the desalted water is produced generally in cogeneration power desalting plants (CPDP) sometimes also called dual-purpose plants.

Some desalination experts (cf. [7]) tend to underestimate the impact of the fuel consumed for desalting seawater on the environment, by considering that thermal desalination in CPDP is minimally responsible for flue gases discharged to at-

mosphere as these discharges can be completely allocated to the power production. However, 22% of the fuel consumed in Kuwaiti CPDP in 2003 was used for desalting as shown further below. The fuel consumed for desalting depends on the desalting method and the way energy is supplied to desalters. Burning fuel for desalting increases environment pollution by producing CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, and other pollutants, with quantities directly related to the amount of fuel consumed. So, desalting clearly contributes to environmental pollution, including global warming. Increasing the efficiency of both power and desalted water productions thus lowers the impact of fuel combustion on the environment.

Tables 1 and 2 show that the consumed power and desalted water in Kuwait are almost doubled every 10 years. The oil production, (main source of income) was 1.983 million barrels/d (724 mil-

lion barrels/y) in 2002, and little more than one tenth of this oil production (75.92 million barrels) was used in the CPDP in 2003. Following the same doubling trend and assuming a constant oil production rate, 20% and 40% of Kuwait total oil production (or total income) would be consumed by the CPDP in 2013 and 2023, respectively. Interpolating this trend (Fig. 1), in about thirty years the total oil production may not be sufficient for providing drinking water (mainly desalted water) and air-conditioning (using more than 75% of electric power consumption) in Kuwait for its population if the present power and water consumption, and oil production, trends continue.

The water consumption in the years 1963, 1973, 1983, 1993, and 2003 were (Table 1) 5.5, 25.5, 86.2, 136.3, and 279.1 MIGD, respectively, an increase of 463.6% between 1963 and 1973,

Table 1  
Installed desalting capacity and daily water consumption in Kuwait [6]

Year	Installed capacity, MIGD*	Daily average consumption, MIGD	Daily per capita fresh water consumption, l/d (IGD)
1963	6.0	5.5	82.8 (18.2)
1973	52.0	25.5	137.4 (30.2)
1983	136.0	86.2	245.0 (53.8)
1993	216.0	136.3	403.0 (88.6)
2003	313.5	279.1	497.3 (109.3)

\*1 IGD = 4,546 l/d; 1MIGD = 10<sup>6</sup> IGD = 4,546 m<sup>3</sup>/d

Table 2  
Electric power production and consumption in Kuwait [6]

Year	Population	Installed power capacity, MW	Million kWh	Max MW	Min MW	Annual kWh/capita	Max load/capita kW
1953		30					
1963		160	508			2,184	
1973	900,965	1,096	4,183			4,643	
1983	1,601,521	3,866	12,499	2,740	5,00	6,747	1.711
1993	1,537,714	6,898	20,178	4,120	9,80	11,162	2.679
2003	2,546,684	9,189	38,577	7,480	2,110	12,992	2.938

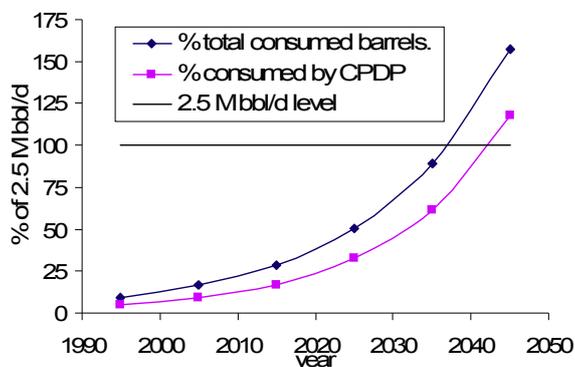


Fig. 1. Percentage of expected fuel consumption by all sectors and by CPDP, and their percentage of total sustainable fuel oil production of 2.5 M-bbl/d, for Kuwait.

238% between 1973 and 1983, 58% between 1983 and 1993, and 105% between 1993 and 2003.

The power consumption increase has paralleled that of the water consumption: in 1963, 1973, 1983, 1993, and 2003 it was (Table 2) 508, 4,183, 12,499, 20,178, and 38,577 million kWh, respectively, an increase of 723% between 1963 and 1973, 199% between 1973 and 1983, 61% between 1983 and 1993, and 91% between 1993 and 2003.

It is noteworthy that the power and water consumption almost more than doubles every 10 years except for the period between 1983 and 1993, when Iraq invaded Kuwait.

The 2004 Kuwait Ministry of Energy (ME) statistical book [6] reported that the consumed fuel energy in 2003 by the Kuwaiti power stations is 410,870 billion BTU (433,491 billion kJ). If one barrel of oil produces 5.71 GJ heat, then the fuel consumed is equivalent to 75.92 million barrels/y. In 2003, Kuwait's oil production was 1.9825 million barrels/d or 724 million barrels/y, and the CPDP oil consumption is almost 10.4%. While current predictions exist that the world oil may be depleted in about 40 years at the current rate of consumption [8], and though no definitive proof for that was given, there should serious concern about oil production depletion even if the oil supply may last much longer, and more efficient de-

salting system as well as more modest rates of power and water consumption should be considered to save Kuwait's income, non-renewable fuel resources, environment, and indeed life itself.

An example of one of the possible solutions to the problem is the fact that the present Kuwaiti power plants' average efficiency is below 38%, yet it can be improved in the future to 60% by employing combined gas/steam turbine cycles (CC). Also, the multi stage flash (MSF) desalting system consumes specific mechanical equivalent energy (containing both pumping energy of about 4 kWh/(m<sup>3</sup> desalted water)\*, and the heat supplied to both the brine heater and steam ejectors) in the range of 20 kWh/m<sup>3</sup>, but future use of reverse osmosis desalting systems (with energy recovery) can reduce this four-fold, to the range of 5 kWh/m<sup>3</sup>.

Furthermore, as described in more detail below, dealing with water as a free resource gives no incentive to utilize it efficiently and promotes un-sustainability.

As a first step in looking for efficient use of energy, this paper is devoted to review the present and possibly-used desalting methods and the way fuel energy passes through to supply the energy needs (either thermal, mechanical, or both) to desalters, and thereby to point out the most efficient systems to adopt, and the less efficient ones to avoid.

## 2. Fuel consumed by desalting seawater in Kuwait in 2003

In 2003, the fuel energy consumed to produce electric power and desalted water in Kuwait was 433.5 million GJ (equivalent to 75.92 million barrels of crude oil based on 5.71 GJ energy content of one barrel). 431 million m<sup>3</sup> desalted water and 35,577 million kWh electric power were produced [6]. The division of the used fuel between the pro-

\* In this paper m<sup>3</sup> always refers to the volume of desalted water

duced power and desalination depends strongly on the allocation method (a general discussion is available in [9]), and the energy efficiency definition (cf. [10]). It is the authors' belief that the power generation efficiency for dual purpose plants,  $\eta_{p1}$ , should be defined as

$$\eta_{p1} \equiv \frac{\text{net electric energy output} + \text{electric energy loss due to thermal energy input to desalters}}{\text{energy of fuel consumed by the dual purpose plant steam generator}} \quad (1)$$

This definition takes into account the fact that the desalination process consumes a lower quality (low temperature, pressure, and exergy) steam compared to that supplied by the steam generator of the CPDP. This gives an average power production efficiency  $\eta_{p1} = 0.38$ , (heat rate = 9,473 kJ/kWh), and thus the fuel charged to power is 337 million GJ (59 million barrels), and to desalted water it is 96.5 million GJ (16.92 million barrels). So, the average fuel energy charged to produce 1 m<sup>3</sup> of water is 224 MJ/m<sup>3</sup> (can be obtained by burning about 5 kg of fuel oil).

The estimated cost of fuel used to desalt seawater in 2003, based on \$60/barrel, is 1015.2 million dollars. Moreover, the consumed fuel in 2003 for power and water added 33,780 tons of CO<sub>2</sub> to the environment.

It is interesting to compare these numbers with those published by the Kuwait Ministry of Energy (ME) report [6], in which the efficiency of power production is defined as

$$\eta_{p2} \equiv \frac{\text{power output}}{\text{fuel energy consumed by the dual purpose plant steam generator} - \text{thermal energy to desalting}} \quad (2)$$

with reported  $\eta_{p2} = 42\%$ , 10.5% higher than  $\eta_{p1}$ . This definition implicitly but erroneously assumes that the desalination process is charged with fuel energy equal to the heat supplied to the desalters, and charged the balance from the total fuel energy input to the power process. In fact the fuel energy is used to generate steam which is used in producing both power from the turbine and thermal energy to the desalters. The logic of Eq. (1) is to find the equivalent work of the thermal energy supplied to the desalters, and added to the power output to get the CPDP total output in terms of work. It is obvious (cf. [10]) that Eq.(1) is more rational to use than Eq. (2) which charges the desalination process as if it is operated directly from fuel fired boilers.

Using that definition, the cost of  $433.491 \times 10^6$  GJ (75.92 million barrels) was reported in [6] to be 1,542.4 million dollars, or \$20.32/barrel, which is rather low relative to international oil market prices of more than 60\$/barrel.

### 3. A forecast and plan for action

Observing past trends of energy consumption in Kuwait, including the energy used for desalination, it is of great interest to foresee the ability of Kuwait to supply its overall energy and desalination needs if those trends are not changed. Table 3 shows the energy consumption trends, by energy sector, in the period 1995–2005, clearly demonstrating exponential growth.

The estimated oil reserves suggest that the sustainable fuel oil production rate in Kuwait is 2.5 M-bbl/d over a 100 years period. Based on the last 10 years trend of the fuel consumption, the estimated future consumption is given in Fig. 1 and Table 4. These show that the end fuel consumption will reach the whole oil production in the year of 2037. Moreover the consumption by the CPDP only can reach the end fuel production rate by the year 2043. To preserve the ability of the next generations, and in fact even of the present

Table 3

Kuwait's local consumption of energy in the main sectors (in thousands barrels) (The Kuwait Ministry of Energy (ME) website <http://www.moe.gov.kw>)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Electricity general sector	42,943	46,771	49,009	55,123	58,042	60,254	63,903	68,130	70,669	75,684	81,689
Oil sector	25,187	24,096	27,140	30,410	32,520	29,450	32,396	33,708	38,439	44,059	41,354
Transportation sector	16,004	16,693	17,422	17,781	18,113	18,182	18,953	20,174	21,974	23,703	25,382
Household sector	1,100	1,110	1,153	1,147	1,173	1,184	1,218	1,281	1,325	1,340	1,550
Total	85,234	88,670	94,724	104,461	109,848	109,070	116,470	123,293	132,407	144,786	149,975

Table 4

Forecasted fuel consumption in thousands of barrels per year by all sectors and by CPDP, and their percentage of total sustainable fuel oil production of 2.5 M-bbl/d for Kuwait (basic data from [6], further analysis by authors)

Year	Total oil consumption (all sectors)		Total oil consumption (CPDP sector)	
	Barrels (in 1000s)	Percentage of total oil production	Barrels (in 1000s)	Percentage of total oil production
1995	85,234	9.34	42,924	4.70
2005	149,945	16.43	81,689	8.95
2015	263,786	28.91	155,463	17.04
2025	464,056	50.86	295,863	32.42
2035	816,374	89.47	563,059	61.71
2045	1,436,179	157.39	1,071,562	117.43

one, to sustain a satisfactory lifestyle, it is obvious therefore that Kuwait, and most other Gulf countries dependant on water desalination, must rapidly start action to drastically reduce the rate of energy consumption in general and the demand for energy consuming products, with water in particular.

The remainder of this paper focuses on a comparison of energy consumption and emissions of fourteen prevailing desalination processes, to point out their sustainability in view of this situation and forecast.

#### 4. Energy rating methods of desalting processes

The desalination industry uses a number of different energy performance criteria, which be-

sides preventing uniformity, also tend to misrepresent rational evaluation, and especially fuel cost allocation to the produced water when dual-purpose (power and water) plants are employed. The gain ratio (GR) and the performance ratio (PR) are the two most commonly applied methods for rating thermal driven desalting systems, such as the thermal vapor compression TVC, multi stage flash MSF, and multi effect boiling MED desalting units.

The GR is the desalted water output ( $D$ ) per kg of supplied heating steam ( $S$ ) defined by  $GR = D/S$ . The GR does not consider the actual heat quantity given by each kg of used steam,  $\Delta h$  (the enthalpy difference across the desalination plant heater), or the actual heat consumed by the desalter. It is more logical is to calculate the heat

required  $Q_d$  per unit mass of desalted water  $D$ , i.e.,  $Q_d/D$ , instead. This was taken into consideration by defining another energy rating parameter, the performance ratio (PR), by changing the  $S$  used in the definition of GR to the associated amount of heat  $Q_d$  based on the standard value of the latent heat of evaporation of water,  $\Delta h_{\text{ref}} = 2,330 \text{ kJ/kg}$  (for example, if the supplied steam enters as saturated vapor and leaves as saturated liquid, at about  $70^\circ\text{C}$ , which is the average temperature of operating thermally driven desalting system), and thereby PR is the desalted water output  $D$  per kg of supplied steam that has the reference latent heat value  $\Delta h_{\text{ref}} = 2,330 \text{ kJ/kg}$ , and then  $\text{PR} = \text{GR}$ .

Both the GR and PR are deficient in that they do not take into consideration the pressure, temperature and quality of the specifically used steam, or the pumping energy consumed by the process. The real value of steam lies in its ability to produce work (its exergy), which increases with both temperature and pressure. A modified performance ratio,  $\text{PR}'$ , which takes the real amount of heat used by the plant,  $Q_d = S\Delta h$ , defined by the actual enthalpy drop  $\Delta h$  of the steam in the brine heater would thus be  $\text{PR}' = \text{PRH} (\Delta h/2330)$ .

This distinction is especially important when evaluating TVC units, which usually use high pressure (and exergy) steam (say at 10–20 bar) compared to the well known multi stage flash MSF and multi effect ME desalting system, and the GR or PR rating, which overlook this fact introduces a significant error.

Obviously the best way to evaluate the performance of any desalting system is to account for the actual *total* fuel energy required (consumed) including the heat and work, to desalt a unit mass or volume of desalted water, ( $Q_f/D$ ), say in  $\text{MJ/m}^3$ ,  $\text{kJ/kg}$ , or  $\text{kg fuel/m}^3$  of desalted water, where the work is calculated in terms of the fuel needed to generate it in say a power plant of 0.36 standard efficiency or by using its exergy value. The same logic was used in a previous desalination sustainability indicators study [11]. The first indicator is

the resource fuel, defined by amount of fuel in kg per  $\text{m}^3$  of desalted water.

Other energy-related sustainability indicators include environmental ones, including the amount of polluting gases emitted during the combustion of the fuel needed for producing one  $\text{m}^3$  of desalted water, such as  $\text{kg CO}_2/\text{m}^3$ ,  $\text{kg SO}_2/\text{m}^3$ , and  $\text{NO}_x/\text{m}^3$ .

## 5. Water desalination in the Gulf area

The renewable water resources in many Middle East countries, especially the Arab Gulf countries, are highly insufficient to satisfy their water needs, and desalination supplies the large shortfall. Table 5 gives the renewable water resource (mostly groundwater) and the percentage of its extraction (and thus consumption), total and per capita of installed desalting capacity for year 2004. The capacity of the MSF and SWRO desalting units installed in the last 10 years are given for countries, where desalted waters are used extensively. The trend of shifting from complete dependence on the MSF systems, to the more efficient SWRO system is clear in the last decade as shown in Table 6 [5].

## 6. Water consumption inflation

The fresh water consumption in Kuwait, of more than 500 l/capita/d (Table 1), is much higher than even in the most developed countries in the world. The potable water consumption per capita per day in USA, Australia, and Canada is in the range of 250 l/capita/d; in Denmark and France is in the range of 180 l/capita/d, and in Germany, Belgium, and Portugal is in the range of 140 l/capita/d [12]. In these countries, the consumed water is related to the water price, which is  $\$0.41/\text{m}^3$  in Canada,  $\$0.5/\text{m}^3$  in USA,  $\$1.17/\text{m}^3$  in France, and  $\$1.81/\text{m}^3$  in Germany [12]. In Kuwait, the data from [6] shows that the amount of fresh water consumed in 2003 was  $463.1 \times 10^6 \text{ m}^3$ , and the ME income from selling that water was  $\$75.816 \times 10^6$ ,

Table 5  
Renewable water resources in some Arab countries, 2004 [6]

Country	Annual renewable source (m <sup>3</sup> /capita)	Annual extraction of renewable water (%)	Total installed desalination capacity (m <sup>3</sup> /d)	Desalination installed capacity/capita (l/capita)	% of the world MSF capacity
Bahrain			516,059	792.7	
Egypt	923	97	303,915	4.7	
Iraq	5,340	43	397,753	16.7	
Jordan	314	32	328,507	65.3	
Kuwait	100	510	2,181,026	1,067.0	12.0
Libya	111	767	859,514	158.9	
Oman	892	24	334,879	136.6	
Qatar			762,932	1,276.0	
KSA	254	164	6,569,172	307.0	29.9
UAE	1,047	299	5,532,777	1,586.0	31.0

Table 6  
Capacities of seawater MSF and SWRO desalination units operated in some Arab countries since 1994 [6]

Countries	Capacities (m <sup>3</sup> /d)	
	MSF	SWRO
Bahrain	136,200	3,600
Kuwait	336,104	
Libya	44,240	
Oman	194,982	2400
Qatar	334,640	
KSA	1,337,508	475,516
UAE	2,522,109	2,518,650

which gives a price of \$0.1637/m<sup>3</sup>. This is 2.5–11 fold less than the cost in the above listed countries, which are also by many orders of magnitude more water-rich. This low price is a major reason for the extremely high rate of water consumption in Kuwait and shows that water is apparently treated by some as a free common resource with almost zero economic value. The under-valuation is in fact even much worse, because as mentioned above, the fuel energy consumed for desalting is 224 MJ/m<sup>3</sup>, resulting in a fuel cost for desalination of \$1.57/m<sup>3</sup> produced fresh water when considering an oil price of \$40/barrel

(\$7/GJ) and \$3.14 for the current oil prices reaching \$80/barrel. The fuel cost to produce 1 m<sup>3</sup> of desalted water is \$2.35 for a barrel cost of \$60/barrel. If the total water cost is twice that of the fuel, then it is \$4.71/m<sup>3</sup>, or 28 times the selling price of \$0.1637/m<sup>3</sup>. Since the total cost of desalted water includes the capital and other operation expenses, the actual cost allocated to the water may be at least two-fold higher. This would be about twenty to thirty times higher than the price charged to the customers! Furthermore, the high amount of fuel consumed for producing power and water leads to environmental damage and degrades natural resources, all of which should be also considered in the determination of the price of the water, and may lead to unsustainable economic development.

The present water production rate in Kuwait can meet water needs for many years to come if the water is consumed wisely. Based on data from developed countries, the basic domestic water needs do not exceed 150 l/capita/d, less than one third of the actual consumption rate in 2003. While we note that it is vital to supply the *basic needs* of water to everyone, irrespective of their income, it is vital also to charge a proper price for any amount of water consumed beyond the basic needs, to help

curb the wasteful use of water, and its associate negative impacts on fuel reserves and on the environment. This means that subsidies should be focused and limited to average people's *basic needs*. Limiting quantities to basic needs help in avoiding the typical rebound effect, where gains from efficient water production may easily be offset by increasing of consumption and waste.

In the present work, the specific fuel energy consumed and the amounts of emitted CO<sub>2</sub>, SO<sub>x</sub>, and NO<sub>x</sub> per m<sup>3</sup> of desalted water are calculated for fourteen different cases. Also, the amount of desalted water produced in each case for the same amount of reference fuel consumed rate (used in Case 1) is calculated.

### 7. Case studies

In view of the sometimes-subtle differences between different performance evaluation and fuel allocation methods, which can lead to very different results as mentioned above, we present our case study calculations in a very explicit way to avoid any misunderstandings.

To estimate the rate of CO<sub>2</sub> emissions, the ratio of carbon in the fuel is assumed equal to be 0.85 kg/kg of fuel, and burning 1 kg of fuel thus produces (0.85×44/12=) 3.1167 kg of CO<sub>2</sub>/(kg fuel).

Similarly the ratio of sulfur in the fuel is assumed equal to 0.012 kg/kg of fuel, and burning 1 kg of fuel thus produces (0.012×64/32=) 0.024 kg of SO<sub>2</sub>/(kg fuel).

In estimating the NO<sub>x</sub> emissions, it is assumed that the plant meets the allowable emission level in the US, which is 0.258 (kg NO<sub>x</sub>)/GJ heat output [13].

#### 7.1. Case 1: Fuel fired boiler driving a thermal vapor compression desalting TVC system.

There are about 127 thermal vapor compression desalting system (TVC) units [5] having an almost 200 MIGD installed capacity in the Middle East Arab countries and Iran. These units are in

general operated with steam supplied directly from fuel fired boilers, having low top brine temperature in the range of 65°C and using falling film horizontal tube evaporators. Most of these units were put in service in the last decade. The only reported units that use steam extracted from turbines are those in Um-Al-Nar and Al-Taweela in UAE [14]. Steam supplied to Al-Taweela units is exhausted from a backpressure turbine at 2.8 bar. In winter, when fewer turbines are in operation and available to supply steam, these desalination plants are directly supplied from the power plant's steam generator through a high pressure (HP) reducing station. Fig. 2 shows a schematic diagram of a TVC unit. It consists of multi-evaporators, steam ejector (thermal compressor TC), and end condenser. The four TVC units at Jebel Dehna, UAE [5] shown in Fig. 2, is Case 1 of this study.

In the analysis of this Case 1, and of the following Case 2, in both of which steam is supplied to the desalting unit(s) directly from the boiler, the following are assumed:

The heat supplied to the desalting unit(s),  $Q_d$ , is equal to the boiler heat output  $Q_b$ , and is equal to the steam mass flow rate  $S_d$  multiplied by the difference between the enthalpy at the inlet  $h_{di}$  and that at the exit  $h_{de}$ , i.e.

$$Q_d = Q_b = S_d (h_{di} - h_{de})$$

The gain ratio,  $GR$ , is defined by the ratio of the desalted water output  $D$  divided by  $S_d$

$$GR = \frac{D}{S_d}$$

The fuel energy,  $Q_{fd}$  supplied to the boiler to produce  $Q_b$ , and  $q_{fd}$  the  $Q_{fd}$  per unit desalted water, are, respectively

$$Q_{fd} = Q_b / \eta_b = m_f \times \text{LHV}$$

$$q_{fd} = Q_{fd} / D = Q_b / (D\eta_b)$$

where  $m_f$  is the fuel mass supply to the boiler, and LHV is the low heating value of the fuel (heat generated by the combustion of 1 kg of fuel, when

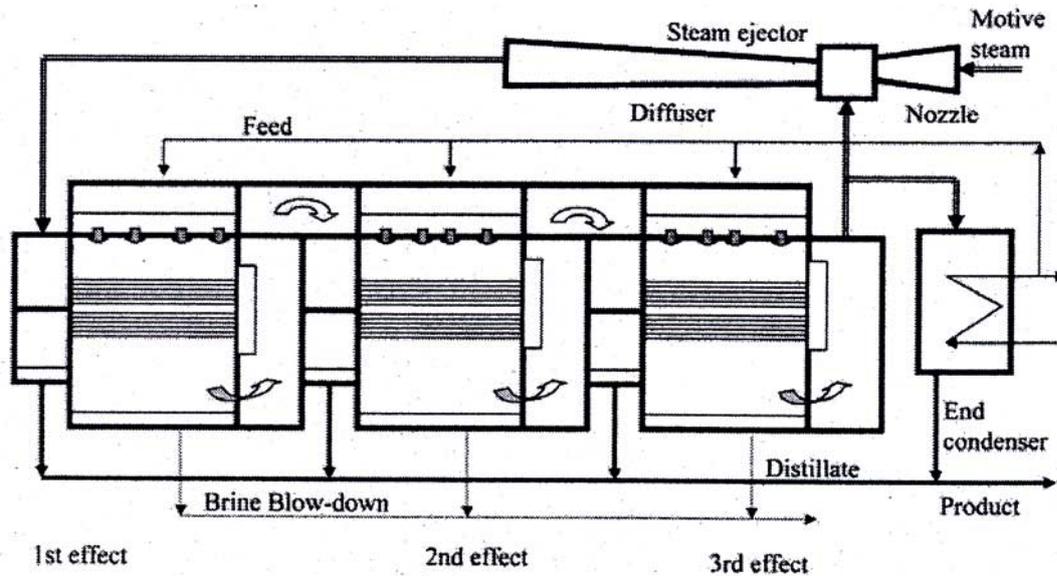


Fig. 2. Multi-effect thermal vapor compression (TVC) desalting system (Case 1).

the water in the combustion is in vapor form), and  $q_{fd}$  is the specific heat per unit distillate due to heat supplied to the desalting units. LHV is considered in the following calculations equal to 40 MJ/kg fuel.

Each desalting system consumes pumping energy  $W_p$  to move its streams, and the specific pumping energy per kg of desalted water is expressed by  $W_p/D$ . To produce the pumping energy from a power plant of thermal efficiency  $\eta_c$ , the specific fuel energy consumed to produce the pumping energy  $q_{fp} = (W_p/D)/\eta_c$ .

The specific fuel energy for the heat and pumping energy is thus  $q_f = q_{fd} + q_{fp}$ .

The fuel energy cost per  $m^3$  desalted water can be calculated by considering the fuel oil cost per barrel is \$60/barrel (or \$10.52 per GJ).

The fuel energy can be transferred to mechanical work in a power plant having efficiency  $\eta_c$ , and thus the fuel energy  $Q_f$  has equivalent mechanical work capability  $= \eta_c Q_f$ .

If the specific fuel energy  $Q_f/D$  is given in MJ/ $m^3$ , then the  $CO_2$  produced by producing 1  $m^3$

$$\text{of desalted water} = (Q_f/D) \times 3.1167/40 (\text{MJ/kg fuel}) = 0.078 (Q_f/D) \text{ kg } CO_2/m^3$$

The  $SO_2$  emitted by producing 1  $m^3$  desalted water is thus  $(Q_f/D) \times 0.024/40 = 0.0006 (Q_f/D) \text{ kg } SO_2/m^3$

In Case 1, the total desalted water output  $D_T = 7,180 \text{ m}^3/\text{d}$  (314.6 kg/s or 5.98 MIGD), and the gain ratio  $GR = 9$ .

This gives:

$$S_d = 34.956 \text{ kg/s.}$$

$S_d$  is supplied to the TVC units as saturated steam of 10 bar, and enthalpy  $h_{di} = 2,778.1 \text{ kJ/kg}$ , and leaves as saturated liquid of  $T = 65^\circ\text{C}$ , and enthalpy  $h_{de} = 272.06 \text{ kJ/kg}$ , then:

$$Q_d = 34.956(2,778 - 272.06) = 87,600 \text{ kW} = 78.6 \text{ MW}$$

$$Q_{fd} = 87.6 / 0.9 = 97.33 \text{ MW}$$

$$Q_{fd} / D = q_{fd} = \frac{97,333}{314.6} = 309.39 \text{ kJ/kg}$$

The estimated specific pumping energy to the

TVC,  $W_p/D = 2 \text{ kWh/m}^3$  (7.2 kJ/kg), and  $q_{fp} = 7.2/0.36 = 20 \text{ kJ/kg}$ .

The total specific fuel energy  $(Q_f/D)_T = q_f = 20 + 309.4 = 329.4 \text{ kJ/kg} = 329.4 \text{ MJ/m}^3$ , (for both heat and pumping energy added), and the total fuel energy for the specified water production rate is thus

$$Q_f = 329.4 \times 314.6 / 1000 = 103.626 \text{ MW.}$$

Assuming a power plant of thermal efficiency  $\eta_c = 0.36$ , the work equivalent of this  $Q_f$  is equal to  $103.626 \times 0.36 = 37.3 \text{ MW}$ , and the equivalent work of the specific fuel energy  $q_{fd} = Q_f/D$  is equal to  $329.4 \times 0.36 = 118.8 \text{ kJ/g} = 32.94 \text{ kWh/m}^3$ .

The fuel energy cost per  $\text{m}^3$  desalted water produced by this TVC, based on \$60/barrel (or \$10.526 per GJ) =  $10.526 \times 329.4 / 1000 = \$3.467/\text{m}^3$ .

$$\text{The CO}_2 \text{ production/m}^3 = 0.078 \times 329.4 = 25.69 \text{ kg CO}_2/\text{m}^3.$$

$$\text{The SO}_2 \text{ production/m}^3 = 0.0006 \times 329.4 = 0.2 \text{ kg SO}_2/\text{m}^3$$

$$\text{The emitted NO}_x \text{ is } 0.3294 \times 0.258 = 0.094 \text{ kg NO}_x/\text{m}^3.$$

The amount of fuel energy used in this Case 1  $(Q_f)_T = 103.6265 \text{ MW}$  will be used in the rest of this paper as a reference rate of fuel energy input to compare the amount of desalted water that can be obtained from the same fuel energy input by the different studied cases.

### 7.2. Case 2: Fuel fired boiler driving a multi stage flash MSF desalting system

The multi-stage flash (MSF) is the main desalting method used in the Gulf area. Most of the existing MSF units are supplied with steam extracted from steam turbines. When no operating turbines (or no turbines at all) exist, steam is supplied directly from boiler through reducing pressure station. In the Shuwaik desalting plant in Kuwait, there are 3 MSF units operated with steam supplied directly from three fuel-fired boilers (Fig. 3), and this is considered here as Case 2.

The data given for this case are:

$$D = 342 \text{ kg/s (6.5 MIGD)}$$

$$\text{The gain ratio GR} = D/S_d = 9.$$

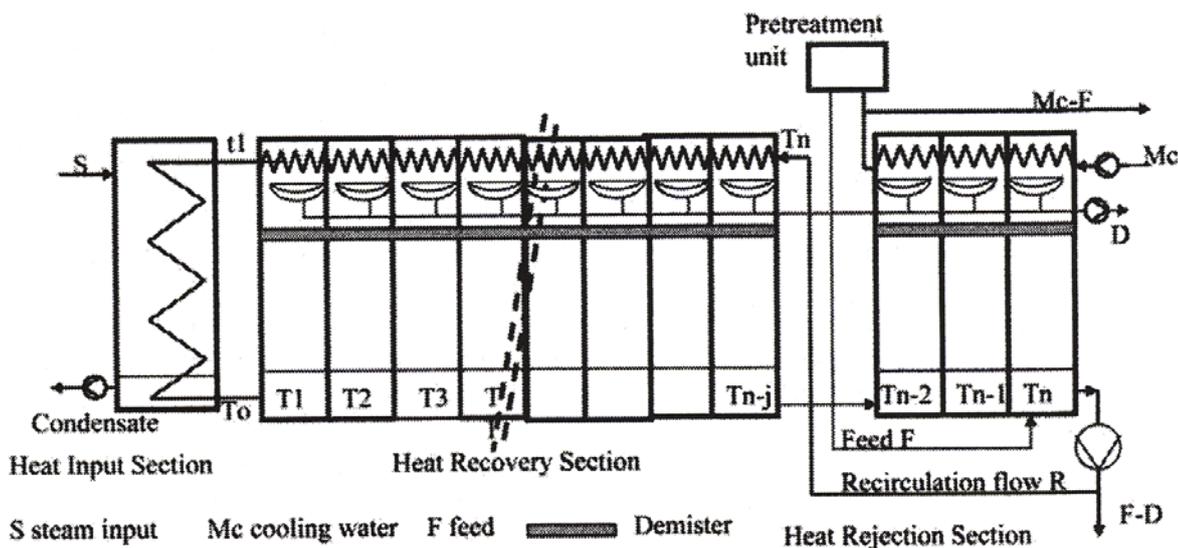


Fig. 3. Multi-stage flash MSF desalting system.

$$S_d = 38 \text{ kg/s}, Q_d = 83.7 \text{ MW}$$

$$Q_{fd} = 93 \text{ MW}$$

$$Q_{fd} / D = q_{fd} = \frac{93,000}{342} = 271.92 \text{ kJ/kg}$$

The estimated specific pumping energy to the MSF = 4 kWh/m<sup>3</sup> (14.4 kJ/kg), and

$$q_{fp} = 14.4/0.36 = 40 \text{ kJ/kg.}$$

The total specific fuel energy  $(Q_f / D)_T = q_f = 40 + 271.9 = 311.9 \text{ kJ/kg} = 311.9 \text{ MJ/m}^3$ , (for both heat and pumping energy added), and the total fuel energy for the specified water production rate is thus  $Q_f = 311.9 \times 342/1000 = 106.67 \text{ MW}$ .

The equivalent work of this  $Q_f$  is thus  $106.67 \times 0.36 = 38.4 \text{ MW}$

The equivalent work of the specific fuel energy  $Q_f/D$  is thus  $311.9 \times 0.36 = 112.284 \text{ kJ/g} = 31.19 \text{ kWh/m}^3$

The fuel energy cost per m<sup>3</sup> desalted water produced by this MSF, based on \$60/barrel (or \$10.526 per GJ) =  $10.526 \times 311.9/1000 = \$3.283/\text{m}^3$

The CO<sub>2</sub> production/m<sup>3</sup> =  $0.078 \times 311.9 = 24.33 \text{ kg CO}_2/\text{m}^3$ .

The SO<sub>2</sub> production/m<sup>3</sup> =  $0.0006 \times 311.9 = 0.187 \text{ kg SO}_2/\text{m}^3$

The emitted NO<sub>x</sub> =  $0.3119 \times 0.258 = 0.0847 \text{ kg NO}_x/\text{m}^3$ .

When the referenced rate of fuel energy input  $Q_{ref} = 103.6265 \text{ MW}$  of Case 1 is applied to Case 2, the rate of desalted water production is 332.24 kg/s, as shown in Table 7.

- Comparing Case 1 with Case 2 indicates that:
1. Although GR = 9 for both cases, the  $(Q_f / D)$  (heat input only) is 309.4 kJ/kg for Case 1, and 271.9 for Case 2. As a result, PR = 8.3677 in Case 1, and 9.52 in Case 2. This confirms that GR indeed is not a good indicator of the heat consumption by the desalters, and considering GR and PR to be the same is incorrect.
  2. The specific pumping energy in Case 2 is double of that in Case 1, and this was not accounted for in ratings by PR or GR.

Table 7  
Summary of the main result for the fourteen studied cases (kg and m<sup>3</sup> are of desalted water)

No.	Case	D for $Q_{ref}$ <sup>*</sup> (kg/s)	$(Q_f/D)_T$ (MJ/m <sup>3</sup> )	CO <sub>2</sub> (kg/m <sup>3</sup> )	SO <sub>2</sub> (g/m <sup>3</sup> )	NO <sub>x</sub> (g/m <sup>3</sup> )	Fuel cost <sup>*</sup> (\$/m <sup>3</sup> )
1	Fuel fired boiler driving TVC	314.6	329.4	25.67	220.4	94.0	3.47
2	Fuel fired boiler driving MSF	332.2	311.9	24.30	209.0	80.5	3.28
3	Steam extracted from steam turbine driving MSF	522.0	198.5	15.47	106.2	40.9	2.08
4	BPST power driving MVC and MED	803.2	129.0	10.05	86.4	33.3	1.35
5	BPST power driving SWRO and MED	1,459.9	71.0	5.53	47.6	18.32	0.75
6	Steam cycle driving MVC	863.6	120.0	9.35	80.4	31.0	1.26
7	Steam cycle driving SWRO	1,727.1	60.0	4.68	40.2	15.5	0.63
8	GT driving SWRO	1,775	58.4	4.55	39.1	15.1	0.62
9	GT driving MVC	887.2	116.8	9.10	78.3	31.3	1.23
10	GT with HRSG driving MSF and SWRO	1,824.7	56.8	4.43	38.1	14.6	0.60
11	GT/ST cycle driving SWRO	2,514.0	41.2	3.21	27.6	16.3	0.43
12	GT/ST cycle driving MVC	1,256.0	82.5	6.42	53.3	21.3	0.87
13	GT/ST cycle with BPST driving MVC and MED	2,579.5	41.9	3.27	28.1	10.8	0.44
14	GT/ST cycle with BPST driving SWRO and MSF	2,427.0	42.7	3.33	28.6	11.0	0.45

\* $Q_{ref}$  = Reference fuel energy = 103.626 MW for TVC, Case 1)

\*\*Fuel cost based on \$60/barrel

- Fuel of high exergy was used to generate low exergy steam in fuel fired boilers for direct supply to the MSF at about 3 bar, or to TVC at 10–20 bar. This is an inefficient way of using fuel, as also demonstrated in the next Case 3.

### 7.3. Case 3: Cogeneration power desalting plant (CPDP) using condensing–extraction steam turbine (CEST) to drive MSF desalination unit(s)

As stated above, the use of the high exergy fuel to generate low exergy steam (as done in Cases 1 and 2) is wasteful process from the thermodynamics viewpoint. It is always better to first reduce the high exergy of the fuel through power production to the exergy level of the steam needed for desalination. This is done by first generating steam at high temperature and pressure (as required for modern steam power plants), expanding it in steam turbines to produce work, and then using the turbine extraction or exhaust steam as the heat supply to the desalting plants. A plant, where steam produces both power (work) and desalted water is known as a co-generation power desalting plant (CPDP), or dual purpose plant. The main merit of the CPDP is saving fuel as compared to two separate plants, one for water desalination and the other for power.

CPDP using steam turbines and MSF desalting units are extensively used in the Gulf area. The steam turbines are either of the condensing steam turbine (CST) or backpressure steam turbine (BPST) type. Each turbine is combined with one or more MSF units. The steam supply to the MSF unit(s) is extracted from a CST (Fig. 4) or exhausted from a BPST. Examples of some CPDP using steam turbines and MSF units in the Gulf area are given in [15]. A typical plant in Kuwait is used here as Case 3. Steam is generated at high pressure around 150 bar and temperature 538°C. The 150 bar pressure is high enough for driving an efficient steam power plant cycle, and low enough for using natural circulation steam generators. The 538°C temperature is the highest al-

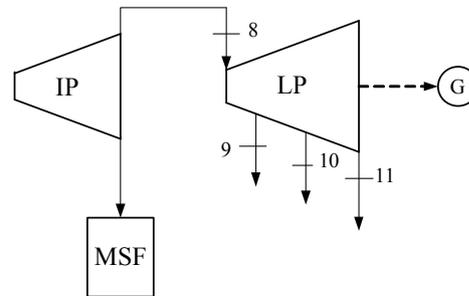


Fig. 4. Condensing–extraction steam turbine (CEST) producing power and driving a MSF desalting.

lowable for fuel oil with sulfuric content. The CPDP plant, shown in Fig. 4 uses a steam generator, a CST steam turbine, and two MSF desalting units. The use of CST in CPDP gives more operation flexibility than back pressure steam turbine. The given plant with CST can produce power at different loads from 75 MW to 300 MW, with and without steam extracted to the MSF desalting unit. In other words, it can work as an SPP (separate power plant) producing 300 MW down to 75 MW electric power; or as CPDP producing 300 MW down to 75 MW, while supplying heat of 196 MW to two MSF desalting units.

The desalted output is 757.7 kg/s (14.4 MIGD). The thermal energy supplied for the desalination is 196 MW, having a specific heat demand  $q_{fd} = (Q_f / D) = 258 \text{ kJ}/(\text{kg desalted water})$ .

Steam is extracted to the desalting unit(s) at rate of 77.22 kg/s from the cross-pipe between the IP and LP (intermediate and low pressures) cylinders. If this extracted steam was expanded in the LP turbine to the condenser, instead of being extracted for desalting, it would have produce more work. This work is considered as turbine work loss due to steam extraction, and its heat equivalent is used in this study as the heat supply to the MSF units. The data for the LP turbine in the referenced plant is given in Table 8. The mass flow rate to the LP turbine is 133.35 kg/s, its power output is 74.66 MW, and thus the specific power production is 560 kW/(kg/s steam). Thus, the lost

Table 8  
Data for the LP turbine (Case 3)

Mass	M (kg/s)	Enthalpy (kJ/kg)
Mass in LP cylinder	$M_8 = 133.35$	$H_8 = 2,940$
Steam extracted to feed heater at point 9	$M_9 = 7.39$	$H_9 = 2,769$
Steam extracted to feed heater at point 10	$M_{10} = 11.13$	$H_{10} = 2,608$
Steam flow to condenser at point 11	$M_{11} = 114.83$	$H_{11} = 2,333$

work due to the extraction of steam before the LP turbine =  $77.22(\text{kg/s}) \times 560(\text{kW}/(\text{kg/s})) = 43.234 \text{ MW}$ .

Considering that the steam has the same enthalpy at the inlets to the LP turbine and desalters,  $h_8 = 2,961 \text{ kJ/kg}$ , and leaves the desalters as condensate at  $100^\circ\text{C}$ ,  $h_f = 419 \text{ kJ/kg}$ , the heat supplied to the desalters =  $77.22(\text{kg/s}) \times (2961 - 419) (\text{kJ/kg}) = 196.29 \text{ MW}$ . In other words, the  $77.22 \text{ kg/s}$  steam having the energy content of  $196.29 \text{ MW}$ , used for desalination, could have been used in the LP turbine to produce the above-calculated  $43.432 \text{ MW}$  power. By being introduced into the MSF units instead, the associated specific (per unit produced water) equivalent work is  $57.06 \text{ kJ}/(\text{kg desalted water})$  (i.e.  $15.85 \text{ kWh}/\text{m}^3$ ) and the associated specific fuel energy input ( $Q_f/D$ ), again assuming that  $\eta_{pp} = 0.36$ , is  $158.5 \text{ kJ/kg}$ . When specific energy for pumping,  $14.4 \text{ kJ/kg}$  ( $4 \text{ kWh}/\text{m}^3$ ), is added, the total specific work is  $71.46 \text{ kJ}/(\text{kg desalted water})$ , ( $19.85 \text{ kWh}/\text{m}^3$ ), the total specific fuel energy ( $Q_f/D$ )<sub>T</sub> becomes  $198.5 \text{ MJ}/\text{m}^3$ . So, the rate of fuel energy used to produce  $756.7 (\text{kg desalted water})/\text{s}$  is  $150.4 \text{ MW}$ . The referenced fuel energy rate  $Q_{ref}$  would produce  $522.05 \text{ kg/s}$  ( $9.91 \text{ MIGD}$ ) of desalted water by this arrangement. The fuel cost is  $\$2.085/(\text{m}^3 \text{ desalted water})$ , based on  $\$60/\text{bbl}$ .

Based on these values, the  $\text{CO}_2$  produced is  $15.47 (\text{kg CO}_2)/\text{m}^3$ .

The amount of emitted  $\text{SO}_2$  is  $0.1062 (\text{kg SO}_2)/\text{m}^3$ , and the emitted  $\text{NO}_x$  is  $0.0409 (\text{kg NO}_x)/\text{m}^3$ .

The results for Case 3 are given in Table 7. Compared with Cases 1 and 2, the Case 3 system saves more than 50% in the total specific fuel

consumption ( $Q_f/D$ )<sub>T</sub>. We note though that the CPDP are designed and built to produce water at an almost constant rate, while the produced power changes according to load, from 27% to full turbine rated capacity. Table 9 shows the ratios of installed, minimum, and maximum water to power demands in some Gulf countries [15]. Since the rate of water demand increase is higher than that of power demand, water plants that produces water only, or plants in which the water production is not related to the power production rate, as given in the next cases, are needed in most Gulf area.

7.4. Case 4: Water-only desalination plants using BPST power to drive both a mechanical vapor compression MVC desalting plant, and, using its exhaust steam heat, a multi effect desalting MED systems (Fig. 5)

In this case, steam from a boiler is supplied to a BPST, with a discharge pressure usually higher than that of the condenser pressure of a conventional condensing turbine. The power output of

Table 9  
Minimum and maximum demand, and installed, water-to-power ratio in some Gulf countries [8]

Country	Min. W/P ratio (m <sup>3</sup> /d)/MW	Max. W/P ratio (m <sup>3</sup> /d)/MW	Installed W/P ratio (m <sup>3</sup> /d)/MW
Kuwait	142	837	175
Bahrain	350	1,580	570
UAE	320	1,170	347

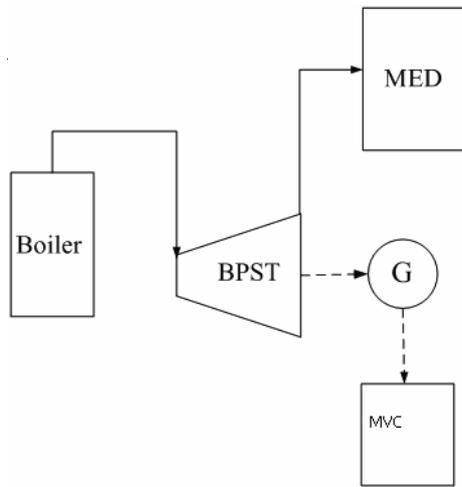


Fig. 5. Back pressure steam turbine (BPST) using its power output to drive mechanical vapor compression MVC desalting plant, and, using its exhaust steam heat to drive multi effect desalting MED systems (Case 4).

the turbine is used to drive the compressor of mechanical vapor compression MVC desalting unit either directly or through its electric power output. In addition, the steam discharged from the turbine at low pressure of 35 kPa is supplied, as the heat source, to the first effect of a multi effect desalting MED system. This case is similar to a desalting system installed on a barge [16] using the same type of MVC and MED desalters systems but at different conditions.

As given before, the steam enters the BPST at 4 MPa and 538 °C, and enthalpy  $h_s = 3,532.7$  kJ/kg, and expands in the turbine to 35 kPa, quality of 0.95, and enthalpy  $h_e = 2,519$  kJ/kg, when it is discharged from the turbine to the MED desalting unit. The steam leaves the MED as condensate (saturated liquid at  $P = 35$  kPa, and  $h_f = 303.4$  kJ/kg), and is directed to the boiler through a de-aerator.

For 100 MW fuel energy supplied to a boiler of 90% efficiency, the boiler heat output

$$Q_b = 90 \text{ MW, and}$$

$$Q_b = m_s (h_s - h_f) = 90,000 \\ = m_s (3534.2 - 303.4)$$

where  $m_s$  is the steam flow rate from the boiler,  $h_s = 3532.7$  kJ/kg is the enthalpy of the steam at the boiler outlet, and  $h_f = 303.4$  kJ/kg is the feed water enthalpy to the boiler.

This gives  $m_s = 27.87$  kg/s as the boiler steam mass flow rate for that 100 MW fuel heat input to the boiler.

If the steam leaving the boiler is supplied to a condensing turbine of 90% isentropic efficiency, and expanded to the condenser pressure at  $P_c = 6.3$  kPa, the steam enthalpy at the condenser inlet  $h_c = 2,333$  kJ/kg, the work output,  $W_c$ , of this condensing turbine, thus is

$$W_c = m_s (h_s - h_c) \\ = 27.87(3532.7 - 2333) / 1000 = 34.436 \text{ MW}$$

This gives the efficiency of the condensing turbine cycle as

$$\eta_c = \frac{W_c}{Q_f} = \frac{34.436}{100} = 0.344$$

In the BPST considered here and in Case 5, the steam enters the turbine at  $h_s = 3,532.7$  kJ/kg, and is discharged at the conditions required by at the MED of  $P = 0.35$  kPa,  $h_e = 2,519$  kJ/kg, and its work output is thus

$$W(\text{BPST}) = m_s (h_s - h_e) \\ = 27.87(3532.7 - 2519) / 1000 = 28.235 \text{ MW}$$

The BPST work output driving the mechanically operated MVC is charged to the desalted water produced by the MVC system, while the work of the condensing turbine  $W_c = 34.346$  MW is charged to the two desalting systems. The heat is supplied to the MED by the steam discharged from the turbine, and this is similar to the steam extracted from the CEST to the MSF units in Case 3. The real value of this steam is its ability to produce work if it has been expanded in a turbine to the condensing pressure. This is consid-

ered as work loss from the turbine due the extraction (or the discharge) of steam before completing its expansion to the condenser condition. This work loss (or work equivalent  $W_e$ ) is charged to the desalted water produced by the MED in Case 4, and by the MSF in Case 3.

This is different than the case when the steam is supplied to the desalting units directly from a boiler (as in Cases 1 and 2), in which the equivalent work was calculated simply by a multiplying the fuel energy  $Q_f$  used to produce  $Q_d$  (heat supplied to the desalting unit) in a boiler of efficiency  $\eta_b$ , which is equal to  $Q_f = Q_d/\eta_b$ , by a typical power cycle efficiency  $\eta_c$ . The equivalent work when the steam is supplied to the desalting units directly from the boiler system is thus  $\eta_c Q_f/\eta_b$ .

Consequently, the equivalent work to be charged to the MED unit is equal to the condensing turbine work output minus the BPST work output = (34.436 – 28.235) = 5.192 MW.

Based on the above, the fuel energy charged to the MVC unit is

$$Q_f(\text{MVC}) = \frac{W(\text{BPST})}{W_c} \times Q_f = \frac{28.235}{34.436} \times 100 = 84.486 \text{ MW}$$

The fuel energy charged to the MED,  $Q_f(\text{MED}) = 100 - 84.486 = 15.532 \text{ MW}$

Typical specific work consumed by the MVC system is 36 kJ/kg (10 kWh/m<sup>3</sup>) by the compressor, and 7.2 kJ/kg (2 kWh/m<sup>3</sup>) by the pumps, and the specific work consumed by the MVC = 36 + 7.2 = 43.2 kJ/kg.

So the MVC desalted water output by the BPST work of 28.235 MW is equal to:

$$D(\text{MVC}) = \frac{28,235}{(36 + 7.2)} = 653.6 \text{ kg/s}$$

and the MVC specific fuel energy  
 $= Q_f(\text{MVC})/D(\text{MVC}) = 84,486/653.6 = 129.26 \text{ kJ/kg}$

For the MED, the performance ratio PR is usually less than, but close to, the number of effects.

A typical 6-effect plant operating in the Gulf has a performance ratio PR = 5.5.

It is noticed here again that there is a difference between the gain ratio

$$GR = \frac{\text{Distillate output}}{\text{Steam supply}} = \frac{D(\text{MED})}{m_s}$$

and the performance ratio PR defined by

$$PR = \frac{2330}{Q_d / D(\text{MED})} = \frac{2330}{m_s (h_e - h_f) / D(\text{MED})} = \frac{D(2330)}{m_s (h_e - h_f)} = GR \frac{2330}{(h_e - h_f)}$$

The heat  $Q_d$  supplied to the MED is equal to:

$$Q_d = m_s (h_e - h_f) = 27.87(2519 - 303.4) = 61,757 \text{ kW}$$

$m_s$  is the steam mass flow rate to the MED (equal to that through the boiler and the turbine), and its enthalpy  $h_e = 2,519 \text{ kJ/kg}$ , (equal to that leaving the BPST), and  $h_f = 303.4 \text{ kJ/kg}$  is the condensate enthalpy leaving the MED (equal to that supplied to the boiler).

For the assumed PR = 5.5,

$$GR = PR \frac{(h_e - h_f)}{2330} = \frac{(2519 - 303.4)}{2330} = 5.23$$

and then the MED water product  $D(\text{MED}) = m_s \times GR = 27.87 \times 5.23 = 45.8 \text{ kg/s}$ .

Since the equivalent work charged to the MED is 5.192 MW due to the heat supplied to the MED, then the specific work done due to the heat supply is  $Q_d = 5192/45.8 = 35.6 \text{ kJ/kg}$ . The specific pumping energy for the MED is 7.2 kJ/kg, and total pumping energy = 7.2 × 45.8 = 1,050 kW, and its corresponding fuel energy is 1,050/η<sub>c</sub> = 3,140 kW. Consequently, the total specific mechanical work is  $w_e(\text{MED}) = 35.61 + 7.2 = 42.81 \text{ kJ/kg}$ , and the specific fuel energy for the MED =  $w_e(\text{MED})/\eta_c = 42.81/0.344 = 128.1 \text{ kJ/kg}$ , where η<sub>c</sub> is the condensing cycle efficiency con-

sidered in this case. The total fuel energy for MVC and MED together,  $Q_f(\text{MED} + \text{MVC})$ , is 103.14 MW, and the total MVC and MED desalted water output  $D$  is 799.4 kg/s.

The total specific fuel energy

$$\frac{Q_f(\text{MVC} + \text{MED})}{D} = q_f(\text{MVC} + \text{MED})$$

for the output of the two systems is 129.02 MJ/m<sup>3</sup>.

The total specific equivalent work  $w_e$  (MVC + MED) is 43.13 kJ/(kg desalted water) based on the above-determined cycle efficiency of 0.334.

The fuel cost is \$1.35/(m<sup>3</sup> desalted water), based on \$60/bbl oil.

The CO<sub>2</sub> emitted to the environment is 10.05 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.129 \times 0.67 = 0.0864$  (kg SO<sub>2</sub>)/m<sup>3</sup>,

and the emitted NO<sub>x</sub> is  $0.129 \times 0.258 = 0.0333$  (kg NO<sub>x</sub>)/m<sup>3</sup>.

When the referenced fuel energy input  $Q_{\text{ref}}$  = 103.6265 MW is used, 803.3 (kg desalted water)/s (15.25 MIGD) can be produced. The results of Case 4 are given in Table 7.

#### 7.5. Case 5: Back pressure steam turbine BPST driving both a seawater reverse osmosis (SWRO) and a multi-effect desalting (MED) system

The more energy-efficient SWRO desalination system can be substituted for the MVC used in Case 4, and the schematic diagram for this case is shown in Fig. 6. The SWRO is assumed to consume 6 kWh/m<sup>3</sup> (21.6 kJ/kg). The power generation conditions of the BPST are the same as assumed and calculated in Case 4 above, and the 28.235 MW output of the BPST in Case 4 thus produces 1,307.2 (kg desalted water)/s when it drives the SWRO system. The MED produces the same 145.8 kg/s as in Case 4 and uses 3.14 MW fuel energy for pumping. The total fuel energy for both SWRO and MED is 103.14 MW, and their total output is 1453 (kg desalted water)/s.

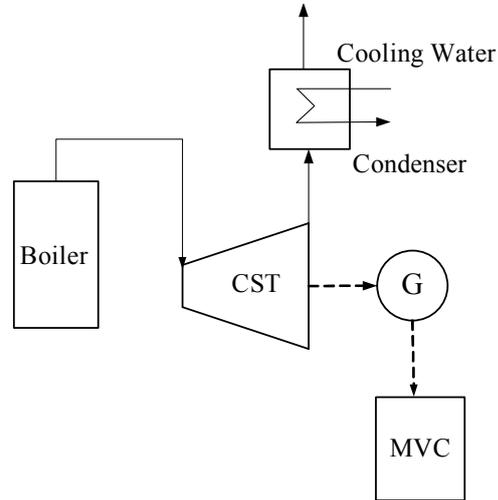


Fig. 6. Condensing steam turbine (CST) driving MVC desalting systems (Case 6).

The total specific fuel energy  $(Q_f / D)_T$  for the two systems together is 70.98 MJ/m<sup>3</sup>.

The fuel cost is \$0.75/m<sup>3</sup>, when the fuel cost is assumed equal to be \$60/bbl.

The CO<sub>2</sub> emitted to the environment is 5.53 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.071 \times 0.67 = 0.0476$  (kg SO<sub>2</sub>)/m<sup>3</sup>, and the emitted NO<sub>x</sub> is

$0.071 \times 0.258 = 0.01832$  (kg NO<sub>x</sub>)/m<sup>3</sup>.

When the referenced fuel input  $Q_{\text{ref}}$  is used, 1,459.9 (kg desalted water)/s (29.7 MIGD) can be produced. The results of Case 5 are given in Table 7.

#### 7.6. Case 6: Steam power cycle driving a MVC desalting system (Fig. 6)

This case is similar to Cases 4 and 5, but the backpressure steam turbine BPST is substituted by a simple condensing steam turbine CST and all the steam turbine power output is used to operate an MVC as shown in Fig. 7. For 100 MW

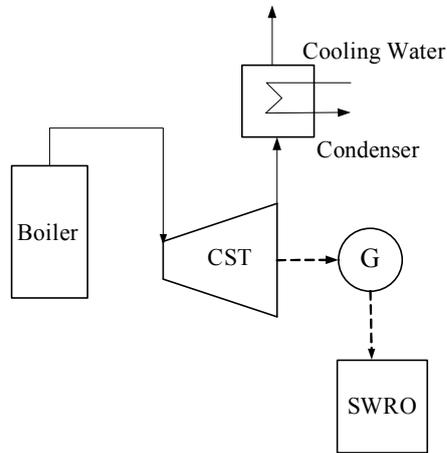


Fig. 7. Condensing steam turbine (CST) driving a SWRO desalting system (Case 7).

fuel energy input to a steam generator of a power plant of net efficiency  $\eta_c = 0.36$ , the total power output is 36 MW. When all this power output is used to operate the mechanically driven MVC, the 100 MW fuel energy is charged to the desalted water output by this desalting method. This is equivalent to power output of 36,000 kW).

As given before, the MVC specific work consumption is: 10 kWh/m<sup>3</sup> for the compressors, 2 kWh/m<sup>3</sup> for the pumps, and thus the total specific work is 12 kWh/m<sup>3</sup> (43.2 kJ/kg).

For 100 MW fuel energy input to the power plant and total power output of 36 MW, the desalted water output  $D(MVC) = 36,000 / 43.2 = 833.33$  (kg desalted water)/s. The total specific fuel energy input  $(Q_f / D)_T = 100,000 / 833.33 = 120$  kJ/kg or MJ/m<sup>3</sup>.

The fuel cost based on \$60/bbl and 5.7 GJ heat/bbl =  $(60 / 5.7) \times (120 / 1000) = \$1.263/\text{m}^3$ .

The CO<sub>2</sub> emitted to the environment is (9.35 kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.12 \times 0.67 = 0.0804$  (kg SO<sub>2</sub>)/m<sup>3</sup>, and

the emitted NO<sub>x</sub> is  $0.12 \times 0.258 = 0.031$  (kg NO<sub>x</sub>)/m<sup>3</sup>.

The referenced fuel energy input  $Q_{ref}$  can produce a distillate output of 863.6 kg/s (16.41 MIGD). The results of Case 6 are given in Table 7.

### 7.7. Case 7: Steam power cycle driving a SWRO desalting system (Fig. 7)

The same CST power plant used in Case 6 is used to drive a SWRO desalting system which consumes 6 kWh/(m<sup>3</sup> desalted water), (21.6 kJ/kg) (Fig. 7). For the same 100 MW fuel energy input to a steam generator of a power plant of net efficiency  $\eta_c = 0.36$ , the system generator output of 36 MW can thus desalt at the rate

$$D(\text{SWRO}) = \frac{W}{\text{specific work}} = \frac{36,000}{6(\text{kWh}/\text{m}^3) [(3600 \text{ kJ}/\text{kWh})/1000 \text{ kg}/\text{m}^3]} = 1666.7 \text{ kg/s}$$

with a specific fuel heat input of

$$\left( \frac{Q_f}{D} \right)_T = \frac{100,000 \text{ kW}}{1666.7} = 60 \text{ kJ}/\text{kg} = 60 \text{ MJ}/\text{m}^3$$

The fuel cost based on \$60/bbl and 5.7 GJ heat/bbl =  $(60 \times 60) / (5.7 \times 1000) = \$0.6316/\text{m}^3$ .

The CO<sub>2</sub> emitted to the environment is 4.68 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.06 \times 0.67 = 0.0402$  kg/m<sup>3</sup>, and

the emitted NO<sub>x</sub> is  $0.06 \times 0.258 = 0.0155$  (kg NO<sub>x</sub>)/m<sup>3</sup>.

When the referenced fuel rate input  $Q_{ref}$  is used, the desalted water rate becomes 1,727.1 (kg desalted water)/s (32.82 MIGD). The results of Case 7 are given in Table 7.

### 7.8. Case 8: Gas turbine (GT) driving a seawater reverse osmosis (SWRO) desalting system (Fig. 8)

The following Cases 8–14 employ a reference

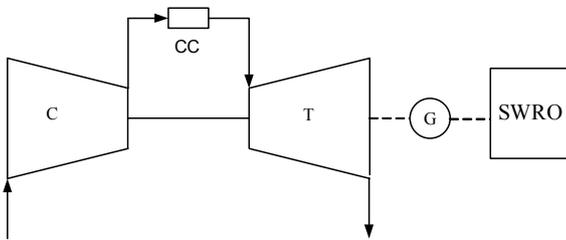


Fig. 8. Gas turbine (GT) driving a SWRO desalting system (Case 8).

gas turbine power plant [17]. Some general description of the use of GT (cf. [18]), are given here preceding the specific analyzed cases. The GT power output can be used to operate mechanically-driven desalting systems such as SWRO or MVC, while its exhaust heat gases can generate steam. This steam can be used to operate thermally-driven desalting system such as MSF, MED, or TVC, as described in the following cases. GT by themselves can be used in simple power cycles producing only power, with cycle efficiency up to about 40%.

The power output of the commercially available GT-s ranges from about 0.5 to 250 MW. They were typically used by utilities for peaking capacity, and ongoing improvements in GT by raising the unit capacity, efficiency, and reliability, increasingly favor their use as base-load power generators.

Large GT-s generate electricity with low  $\text{NO}_x$  emissions, in the single digit ppm range, either with catalytic exhaust cleanup or lean pre-mixed combustion. Because of their relatively high efficiency and reliance on natural gas as the primary fuel, gas turbines emit substantially less  $\text{CO}_2$  per kWh generated than any other fossil fuel technologies in general commercial use. They are used extensively in industry to drive pumps, compressors, and other large mechanical equipment, and many facilities use turbines to generate electricity for use on-site. When used to generate power on-site, GT-s are often used in the CHP mode, with heat used for winter and summer air conditioning.

Combined heat and power (CHP) plants, (usually called cogeneration power desalting plant CPDP when the process heat is used by desalting units), consist of a simple cycle gas turbine combined with heat recovery steam generator HRSG (or sometimes called waste heat boiler WHB). The HRSG recovers the heat content of the hot gases leaving the GT to useful thermal energy in the form of steam. The CHP utilization factor UF, defined as the heat plus power outputs divided by the fuel energy input, or

$$UF = \frac{Q_d + W}{Q_f}$$

can reach up to 70–80%.

If high-pressure steam is generated in the HRSG of the GT, it can be used to drive a steam bottoming cycle in combined gas/steam turbine cycles (CC), thus adding the steam turbine power output to that of the GT, and producing a higher overall power output. Such gas/steam combined power cycles are the most efficient power plants, with current efficiencies up to 60%, and rising.

A well-known gas turbine GE model LM6000 is used in the following Cases to show how a commercial GT can be used to operate different types of desalting system [17]. The data of the LM6000 GT are given in Table 10 for the simple and CHP GT systems.

In Case 8, the typical General Electric LM6000 GT is used to operate a SWRO desalting system. The SWRO consumes  $6 \text{ kWh/m}^3$  (Fig. 9). The turbine has a 40 MW net power output, 37% efficiency, and thus its fuel input rate is  $Q_f = 108.108 \text{ MW}$  at the ISO conditions. The SWRO desalted water output is thus

$$D = \frac{40,000}{(6 \times 3.6)} = 1852 \text{ (kg desalted water)/s}$$

(35.2 MIGD), and the total specific fuel energy

$$\left( \frac{Q_f}{D} \right)_T = \frac{108,108}{1852} = 58.4 \text{ kJ/kg (MJ/m}^3\text{)}.$$

Table 10  
Data for the General Electric Co. LM6000 CHF gas turbines

Cost and performance characteristic	LM6000
Electricity generation capacity (MW)	40
Total installed cost (year 2000 \$/kW)	\$785
Electric heat rate (kJ/kWh) HHV	9,729.72
Electrical efficiency (%)	37
Fuel input (MW)	108.108
Required fuel gas pressure (bar)	30
CHP characteristics	
Exhaust flow (kg/s)	120.20
GT exit temperature (°C)	456.67
HRSG exhaust temperature (°C)	137.78
Steam output, kg/s	16.19
Steam output, MW	40.1
Total CHP efficiency (%) HHV	74
Power to heat ratio	1.00
Net heat rate (kJ/kWh)	5,217.19
Effective electrical efficiency (%)	69

The fuel cost is \$0.615/(m<sup>3</sup> desalted water), when calculated for \$60/bbl and 5.7 GJ heat/bbl.

The emitted CO<sub>2</sub> is 4.55 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is 0.0584 × 0.67 = 0.03913 (kg SO<sub>2</sub>)/m<sup>3</sup>, and

the emitted NO<sub>x</sub> is 0.0584 × 0.258 = 0.01507 (kg NO<sub>x</sub>)/m<sup>3</sup>.

When the referenced fuel rate input  $Q_{ref}$  = 103.6265 MW is used, the desalted water rate is

$$D = \frac{103,626}{108,108} \times 35.2 \text{ (kg desalted water)/s} = 33.74 \text{ MIGD.}$$

The results of Case 8 are given in Table 7.

7.9. Case 9: Gas turbine GT power plant driving an MVC desalting system (Fig. 9)

In this case, the 40 MW power output of the LM6000 GT is used to drive an MVC desalting system, which consumes 12 kWh/m<sup>3</sup> by the compressor and pumps. The rate of fuel input is 108.108 MW at the ISO conditions. So, the MVC desalted water output is

$$D = \frac{40,000}{(12 \times 3.6)} = 926 \text{ (kg desalted water)/s} \text{ (17.6 MIGD)}$$

and the total specific fuel energy

$$\left( \frac{Q_f}{D} \right)_T = \frac{108,108}{926} = 116.8 \text{ kJ/kg (MJ/m}^3\text{)}.$$

The fuel cost based on \$60/bbl and 5.7 GJ heat/bbl = (60/5.7) × (116.8/1000) = \$1.23/m<sup>3</sup>.

The CO<sub>2</sub> emitted to the environment is 9.1 (kg CO<sub>2</sub>)/m<sup>3</sup>,

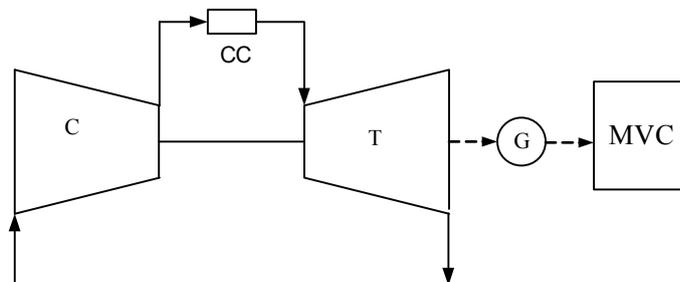


Fig. 9. Gas turbine (GT) driving a MVC desalting system (Case 9).

the emitted  $\text{SO}_2$  is  $0.1168 \times 0.67 = 0.0783$  (kg  $\text{SO}_2$ )/ $\text{m}^3$ , and

the emitted  $\text{NO}_x$  is  $0.1168 \times 0.258 = 0.0313$  (kg  $\text{NO}_x$ )/ $\text{m}^3$ .

The amount of desalted water for the referenced fuel input is 887.2 (kg desalted water)/s (16.87 MIGD).

The results of Case 9 are given in Table 7.

7.10. Case 10: Gas turbine (GT) with a heat recovery steam generator (HRSG) driving both SWRO and MSF desalination plants (Fig. 10)

In this case, the GT power output is used to operate a SWRO desalting plant, and the heat of the GT exhaust gases is used to produce steam by an unfired HRSG. The steam drives an MSF desalting unit. This arrangement is used in many Gulf countries [15].

The HRSG steam output of 16.19 kg/s can operate an MSF unit [17], which consumes 258 (kJ heat)/(kg desalted water) as in Case 3. The

GT power output is 40 MW. The thermal energy recovered by the generated steam from the hot gases is  $Q_d = 40.1$  MW obtained from the HRSG and supplied to the MSF units.

$$Q_d = S(h_s - h_p)$$

where  $S$  is the steam flow rate to the MSF unit(s),  $h_s$  and  $h_p$  is the enthalpies of the steam and its condensate from the MSF unit(s), respectively. This heat produces  $40,100 / 258 = 155.4$  (kg desalted water)/s by an MSF unit. The required pumping energy for the MSF unit, at 14.4 kJ/(kg desalted water), is  $14.4 \times 155.4 / 1000 = 2.238$  MW, and this work is deducted from the 40 MW power output of the GT. So, the net power available to drive the SWRO plant is  $40 - 2.238 = 37.76$  MW. The 37.76 MW net power of the GT which can produce desalted water from the SWRO equal to:

$$D(\text{SWRO}) = \frac{37,760}{(6 \times 3.6)} = 1748 \text{ (kg desalted water)/s.}$$

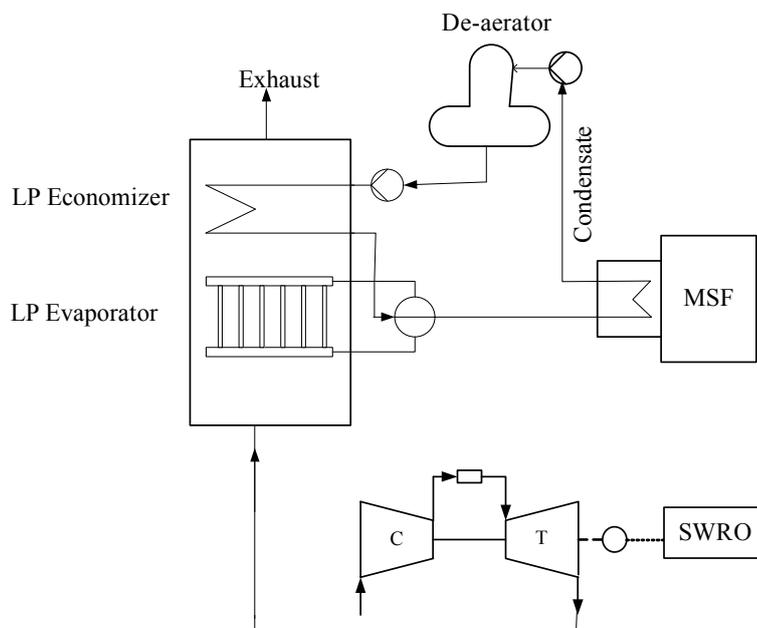


Fig. 10. Gas turbine (GT) with HRSG driving MSF and SWRO desalting systems (Case 10).

The total desalted water output by both MSF and SWRO is 1,903.6 kg/s (36.18 MIGD), and the total specific fuel energy

$$\left(\frac{Q_f}{D}\right)_T = \frac{108,108}{1903.6} = 56.8 \text{ MJ/m}^3.$$

The fuel cost based on \$60/bbl and 5.7 GJ heat/bbl =  $(60/5.7) \times (56.8/1000) = \$0.598 \text{ m}^3/\text{m}^3$ .

The CO<sub>2</sub> emitted to the environment is 4.425 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.0568 \times 0.67 = 0.0381 \text{ (kg SO}_2\text{)/m}^3$ , and

the emitted NO<sub>x</sub> is  $0.0568 \times 0.258 = 0.01465 \text{ (kg NO}_x\text{)/m}^3$ .

When the referenced fuel rate input  $Q_{ref} = 103.6265 \text{ MW}$  is used, the desalted water rate becomes  $(103,626/108,108) \times 36.18 \text{ (kg desalted water)/s} = 34.616 \text{ MIGD}$ .

The results of Case 10 are given in Table 7.

7.11. Case 11: Combined gas/steam power cycle (CC) driving a SWRO desalting system (Fig. 11)

In this arrangement, a bottoming steam cycle, containing a HRSG, is added to the GT to form a

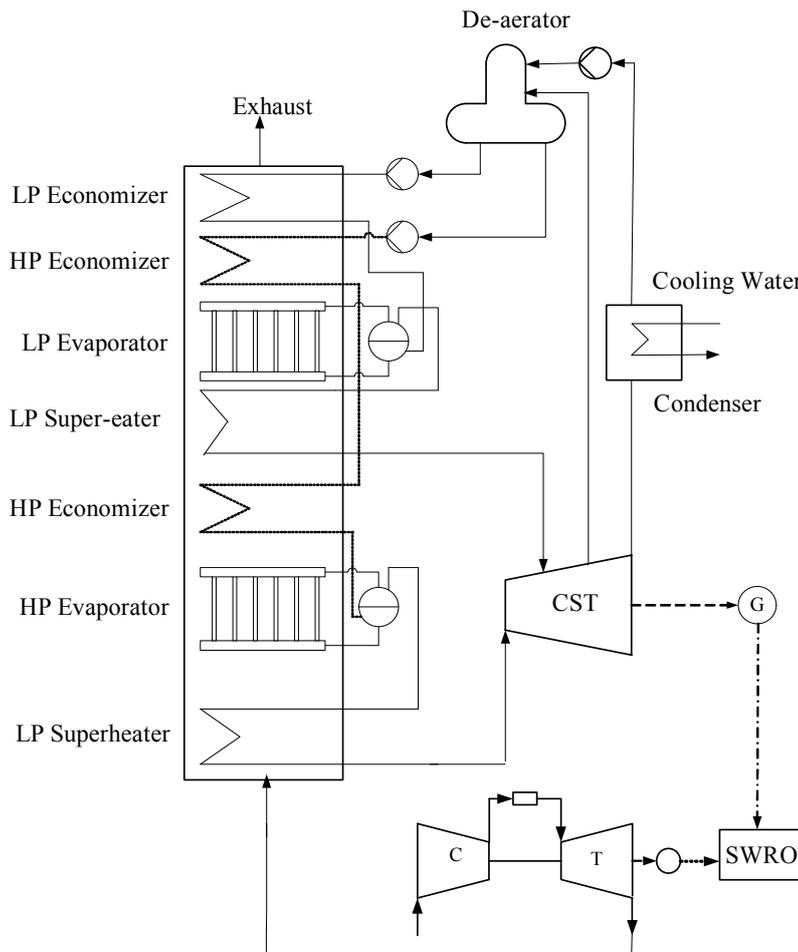


Fig. 11. Combined gas/steam power cycle (CC) driving a SWRO desalting system (Case 11).



When the referenced fuel rate input  $Q_{ref} = 103.6265$  MW is used, the desalted water rate becomes  $(103,626/108,108) \times 49.84$  (kg desalted water)/s = 47.75 MIGD.

The results of Case 11 are given in Table 7.

#### 7.12. Case 12: Combined gas/steam power cycle (CC) driving a MVC desalting system (Fig. 12)

In this arrangement, the same combined cycle of Case 11 drives a MVC desalting system. The total power output is 56.645 MW and the desalted water output is 1,311.2 (kg desalted water)/s (24.92 MIGD), based on the 12 kWh/(m<sup>3</sup> desalted water) compressor and pumping energy requirement. The fuel added to the GT is 108.108 MW and consequently, the total specific fuel input is 82.5 MJ/m<sup>3</sup>.

The fuel cost based on \$60/bbl and 5.7 GJ heat/bbl =  $(60/5.7) \times (82.5/1000) = \$0.868/\text{m}^3$ .

The CO<sub>2</sub> emitted to the environment is 6.42 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.0825 \times 0.67 = 0.0553$  (kg SO<sub>2</sub>)/m<sup>3</sup>, and

the emitted NO<sub>x</sub> is  $0.825 \times 0.258 = 0.0213$  (kg NO<sub>x</sub>)/m<sup>3</sup>.

When the referenced fuel rate input  $Q_{ref} = 103.6265$  MW is used, the desalted water rate becomes  $(103,626/108,108) \times 24.92$  (kg desalted water)/s = 23.887 MIGD.

The results of this Case are given in Table 7.

#### 7.13. Case 13: Combined gas/steam power cycle (CC) with backpressure steam turbine BPST driving both a SWRO and a MED desalting system (Fig. 13)

This case is similar to Case 12 but the steam turbine is a BPST, exhausting steam at 30 kPa to drive a low temperature multi effect boiling MED

system. The characteristics of the MED is similar to that in Case 4, namely, 6 effects, PR = 5.5, 2 kWh/m<sup>3</sup> pumping energy, brine top temperature = 60°C, and steam supply equal to 16 kg/s. The steam turbine power output is 14.45 MW, lower than the 16.465 MW of condensing turbine Case 12, because the steam in this case exits the turbine at  $P = 30$  kPa and not at the condenser pressure of 10 kPa. The MED distillate output is 88 (kg desalted water)/s. The pumping power required for the MED unit is 0.634 MW. So, the net steam turbine power output after supplying the pumping energy to the MED system is 13.82 MW. The SWRO output due the power input of 40 MW by GT and 13.82 MW by BPST is 2,491.5 kg/s. The total desalted water production rate is 2579.5 (kg desalted water)/s (49.02 MIGD).

The total specific fuel energy is 41.91 MJ/m<sup>3</sup>. For the referenced fuel input  $Q_{ref}$ , the desalted output is corrected to 2472.6 kg/s (44.99 MIGD). It is noted here that the decrease of steam power output due to use of the backpressure steam turbine, of 2.015 MW, can be considered as the real work loss due to the use of MED desalting plant, and specific equivalent work due the heat added is 22.9 kJ/kg (6.36 kWh/m<sup>3</sup>), and when adding the 2 kWh/m<sup>3</sup> for pumping, the total equivalent work of MED product is 8.36 kWh/m<sup>3</sup>.

The fuel cost based on \$60/bbl and 5.7 GJ heat/bbl =  $(60/5.7) \times (41.91/1000) = \$0.4412/\text{m}^3$ .

The CO<sub>2</sub> emitted to environment is 3.27 (kg CO<sub>2</sub>)/m<sup>3</sup>,

the emitted SO<sub>2</sub> is  $0.04191 \times 0.67 = 0.0281$  (kg SO<sub>2</sub>)/m<sup>3</sup>, and

the emitted NO<sub>x</sub> is  $0.04191 \times 0.258 = 0.0108$  (kg NO<sub>x</sub>)/m<sup>3</sup>.

When the referenced fuel rate input  $Q_{ref} = 103.6265$  MW is used, the desalted water rate becomes  $(103,626/108,108) \times 49.02$  (kg desalted water)/s = 46.997 MIGD.

The results of Case 13 are given in Table 7.

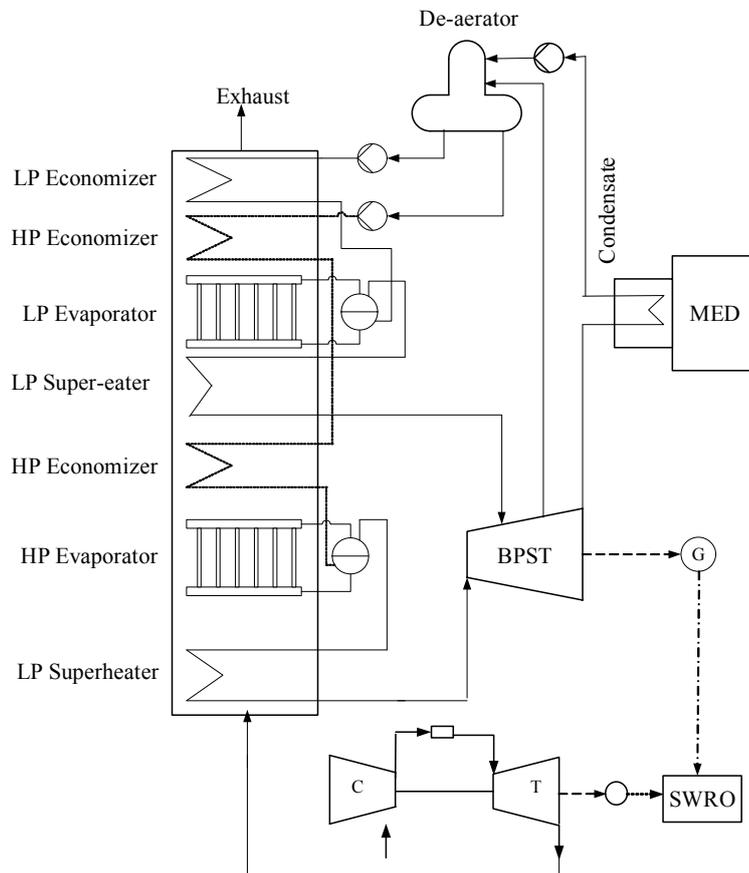


Fig. 13. Combined gas/steam power cycle (CC) with backpressure steam turbine BPST exhaust driving MED desalting, while the net power output driving SWRO system (Case. 13).

*7.14. Case 14: Combined gas/steam power cycle (CC) with backpressure steam turbine (BPST) driving both SWRO and MSF desalting systems (Fig. 14)*

This case is similar to the Al-Taweela plant [19], where combined gas/steam turbines cycles have bottoming backpressure steam turbines that exhaust their steam to drive multi-stage flash MSF desalting units. The plant has three gas turbines with power output equal to 228 MW each at ISO conditions and 185 MW at the corrected 46°C ambient temperature, 1190°C turbine inlet tem-

perature (TIT), compressor pressure ratio of 16 with 17 stages, and the GT turbine has 4 stages. The GT can operate with distilled oil or natural gas.

Three HRSG-s produce 115 kg/s steam each at 70 bar and 522°C. Two backpressure steam turbines are used, and each has power output of 111 MW, throttling conditions (i.e. the turbine inlet condition) of 520°C, 66.5 bar, and exhaust pressure of steam supply to the MSF unit of 3.5 bar.

Four MSF desalting units are used, and each has a 12.5-MIGD (657.7 kg/s) capacity, gain ratio (GR) = 7.7, specific heat consumption of

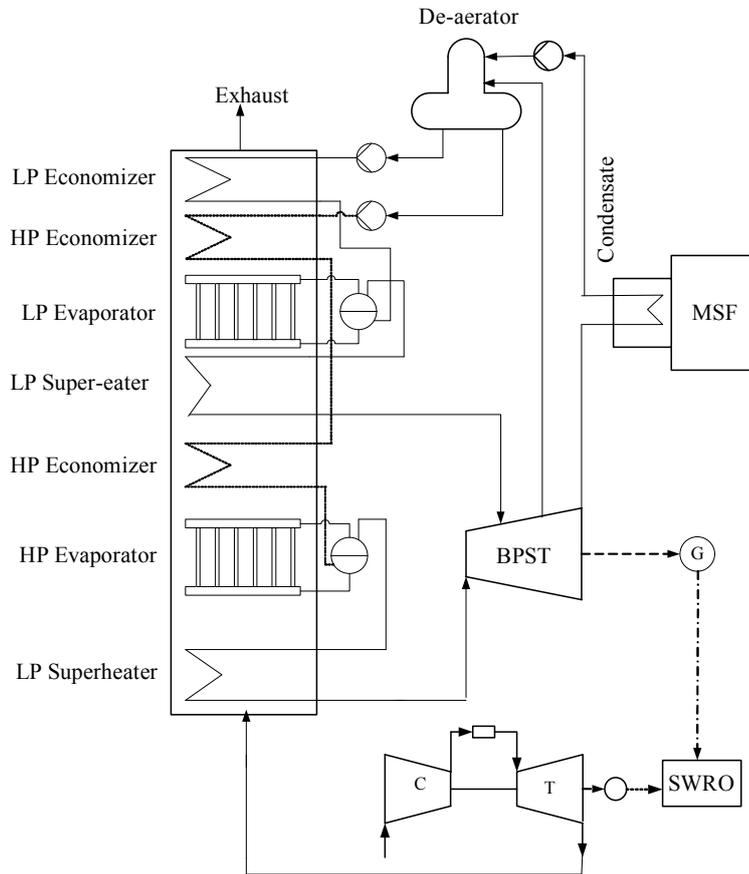


Fig. 14. Combined gas/steam power cycle (CC) with backpressure steam turbine (BPST) driving both SWRO and MSF desalting systems (Case 14).

290 kJ/(kg desalted water), rated top brine temperature of 110°C, feed water salinity of 45,100 mg/l, and reported extremely low specific pumping work of 3.3 kWh/m<sup>3</sup>, (the typical cases in Kuwait reporting 4–4.5 kWh/m<sup>3</sup> pumping energy, and it seems here that the recirculation pumps are driven directly by variable steam turbine, which consumes less energy, but not used typically at least in Kuwait.)

The plant power output from the gas turbines is 555 MW with fuel energy input = 1,586.71 MW. The MSF units of total 50 MIGD (2,630 kg/s) capacity consume 31.2444 MW pumping energy. The backpressure steam turbine BPST power out-

put is 222 MW. Deducting the MSF pumping work from the BPST power output, the BPST net work is 190.7556 MW. The net total power output available from the gas turbines and BPST is thus 745.7556 MW. While this power output of the Al-Taweela plant is not intended to drive a SWRO desalting plant, it is capable of producing 34,525.72 (kg desalted water)/s from a SWRO system if it were used for that. Consequently, the total desalted water that can be obtained from this plant by MSF and SWRO desalting systems together is 37,155.72 kg/s (706.17 MIGD), by the fuel heat input of 1,586.71 MW. This gives an overall specific fuel energy demand of 42.68 MJ/m<sup>3</sup>.

Fuel cost based on \$60/bbl and 5.7 GJ heat/bbl =  $(60/5.7) \times (42.68/1000) = \$0.4493/\text{m}^3$ .

The amount of  $\text{CO}_2$  emitted is  $3.3 \text{ (kg CO}_2\text{)/m}^3$ ,

the emitted  $\text{SO}_2$  is  $0.0427 \times 0.67 = 0.02861 \text{ (kg SO}_2\text{)/m}^3$ , and

the emitted  $\text{NO}_x$  is  $0.0427 \times 0.258 = 0.011 \text{ (kg NO}_x\text{)/m}^3$ .

When the referenced fuel rate input  $Q_{\text{ref}} = 103.6265 \text{ MW}$  is used, the desalted water rate becomes  $(103,626/1586.71) \times 706.17 \text{ (kg desalted water)/s} = 46.14 \text{ MIGD}$ .

The results of Case 14 are given in Table 7.

## 8. General comments on the energy consumptions by desalting systems

It is well known that:

1. The single purpose thermal desalination plants that utilize boiler raised steam directly are less efficient than dual purpose water and power plants that expand the boiler raised steam within a turbine before feeding it to the desalination plant. However single purpose desalting plant, like MSF Shuwaikh plant, is still in operation. Also other TVC units in the Gulf area and Libya are still operated with steam directly supplied directly from fuel fired boilers such as Case 1.
2. The seawater reverse osmosis SWRO desalting method is the most energy efficient desalting system. However, the only seawater desalting method used in Kuwait is the multi stage flash system MSF system (of  $1.5 \text{ Mm}^3/\text{d}$  total capacity), while only 30 MIGD ( $137 \times 10^3 \text{ m}^3/\text{d}$ ) SWRO is under construction now.
3. The combined cycle gas turbine–steam turbine (GT/ST) power plant has a higher thermal efficiency than any other power plant. However, more recent power plants addition is a simple gas turbine cycle.
4. The specific energy consumptions used in this paper is not for the most efficient desalting plants. Examples are:

- a TVC plants are capable of utilizing motive steam with pressures as low as 2 bar and, with a suitable number of effects, can reach gain ratios (GR) of 12–14. The paper itself (page 17) reports that the Al Taweela TVC units use turbine extraction steam at 2.8 bar. The TVC fuel consumption figures in the study, however, are based on a GR of 9 and enthalpies corresponding to a motive steam supply pressure of 10 bar (page 19). Also, since as thermal plants' GRs increase their cooling water requirements and pumping energy consumptions decrease, figures of 1.2–1.5 kWh/m<sup>3</sup>, rather than 2 kWh/m<sup>3</sup>, should apply.
- b MED plants, also with a suitable number of effects, as would be warranted with today's high fuel costs (that are even higher than the paper's utilized fuel cost, 90–100 US\$/barrel vs. 60 US\$/barrel) can provide GRs of 9–10 rather than 5.5, as used in the paper's calculations (a huge difference!).
- c MVC plants are available today with total electrical energy consumptions of 8–9 kWh/m<sup>3</sup>, yet the paper bases its MVC fuel consumption calculations on 12 kWh/m<sup>3</sup>.
- d Even with the higher salinity Gulf seawater, current SWRO plants achieve specific energy consumption figures on the order of 4 kWh/m<sup>3</sup>, rather than the 6 kWh/m<sup>3</sup> used in the study.

The results obtained strongly depend on the assumed typical desalination plant efficiencies, and we used the best current information on their values. These efficiencies are gradually improving, and in the same way that SWRO efficiency improved with the introduction of energy recovery equipment, the efficiency of distillation processes may increase significantly, by such improvements as, for one example, nano-filtration pretreatment which may more than double the current distillation top temperatures and consequently the process efficiencies. While changes

in these efficiencies would change the results, they would not change the conclusion that higher efficiency power generation systems, such as the combined GT/ST cycles studied here, are the most desirable for efficient use of fuel.

While the current study focused on the environmental sustainability effects of the fuel use for desalination, it should be kept in mind that other important sustainability criteria for water desalination include the brine discharges from the plants. These discharges will be at temperatures higher than that of the sea, and will have concentrations of seawater salts, heavy metals, and various water treatment chemicals, that are much larger than the feed seawater. These should, of course, be studied further.

## 9. Conclusions

The paper presents series of energy and fuel consumption calculations for 14 combinations of power and desalination plants and comparing their numerical results.

The energy consumed by each desalting method was calculated based on the real fuel energy consumed to generate the thermal energy and/or the pumping work required by the desalting units. It was shown that the present rating methods of performance ratio or the gain ratio are not suitable to take into account the pumping work and the exergy of the thermal energy supplied to the desalting units. The corresponding equivalent work of the consumed fuel energy (for both thermal and pumping work) was than calculated and used for rating each method.

The study focuses on energy use and its cost; and related emissions. It does not consider overall plant economics that would include capital and non-energy operating costs. An overall economic analysis would be necessary for choosing plants, but there are two important reasons why a focus on energy alone is of sufficient importance: (1) the future availability of fuel sources for satisfying the rapidly increasing demand, including that for fresh water, and (2) the rapidly increasing cost

of fuel which makes the energy portion of the desalted water cost more dominant. In fact, other economic considerations may dilute the main purpose of this study.

It was shown how non-uniform and improper definitions of dual purpose desalination plant performance criteria and fuel/cost allocation methods could underestimate the true costs of desalted water and of the associated impact of emissions.

General comparison between all the cases considered (Table 7) indicates the following:

1. Operation of the TVC, MSF, and MED by steam directly supplied from fuel operated boilers, as cases 1, and 2 is inefficient should be avoided.
2. The SWRO is currently the most energy efficient desalting system and all the efforts should be devoted to solve its pretreatment problems and its full applications.
3. The MVC is the most efficient distillation system, and more effort should be done towards increasing its unit capacity by developing compressors of large sizes, and decreasing its mechanical energy consumptions by raising the heat transfer coefficients in their evaporators and pre-heaters.
4. Using high efficiency combined GT/ST power production integrated with any of the considered desalination system consumes the least energy and thus incurs the lowest energy cost: the lowest of all the 14 cases considered, at \$0.43/m<sup>3</sup> is a GT/ST driving SWRO desalination (Case 11). However, GT/ST driving combined SWRO/MSF desalination systems (Case 14), or with combined MVC/MED systems (Case 13), produce an energy efficiency and water costs nearly the same as that, at \$0.43/m<sup>3</sup> and \$0.45/m<sup>3</sup>, respectively, but with somewhat higher system complexity.

## Symbols

BPST	—	Back pressure steam turbine
CC	—	Combined gas/steam turbine power cycles

CHP	—	Combined heat and power plant
CPDP	—	Cogeneration power desalting plant
CST	—	Condensed type steam turbine
$D$	—	Distillate (product water) flow rate, kg/s
GR	—	Gain ratio, distillate/steam $D/S$
GT	—	Gas turbine
$h$	—	Enthalpy, kJ/kg
HHV	—	Fuel high heating value
HRSG	—	Heat recovery steam generator
IP	—	Intermediate pressures
$L$	—	Latent heat, kJ/kg
LP	—	Low pressure steam turbine cylinder or low pressure
$m_s$	—	Steam flow rate, kg/s
PR	—	Performance ratio
$Q_b$	—	Heat supplied by the boiler, kJ/s (kW), or MJ/s (MW)
$Q_d$	—	Heat input to desalting system, kJ/s (kW), or MJ/s (MW)
$Q_f$	—	Fuel heat, kJ/s (kW), or MJ/s (MW)
$Q_{ref}$	—	Reference fuel energy = 103,626.5 kW ( $Q_f$ for fuel fired boiler driving TVC, Case 1).
$(Q_f/D)_T$	—	Total specific fuel energy, kJ/kg or MJ/m <sup>3</sup>
$S$	—	Steam supply mass flow rates (kJ/s)
SPD	—	Single purpose desalting plant
SPPP	—	Single purpose power plant
ST	—	Steam turbine
TC	—	Thermal compressor (steam ejector)
$W$	—	Work output or consumed, kJ
$W_e$	—	Equivalent work, kJ
$w_e$	—	Specific equivalent work, kJ/(kg desalted water)
WHB	—	Waste heat boiler
$\eta$	—	Efficiency

#### Subscripts

$d$	—	For desalting unit
$f$	—	Fuel
$pp$	—	Power plant
$s$	—	Steam
$T$	—	Total

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