Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.957982

55 (2015) 2423–2436
August

Taylor & Francis
Taylor & Francis Group

Economic assessment of thermal desalination processes

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Received 23 March 2014; Accepted 16 June 2014

ABSTRACT

Cost of desalinated water is a very important factor in evaluating the desalination plant economics and reliability, especially if the plant gets older in operation. The potential increase of shutdown maintenance schedules and reduction of annual production capacity are the major factors because they increase the water cost. This comprehensive study has been carried out to evaluate more than 24 thermal desalination plants in operation in four oil and gas facilities in Libya. Three thermal technologies are mainly used in the oil and gas sector in Libya: multi-stage flashing and multi-effect evaporation with/without thermal vapor compression (MEE/MEE-TVC). Some of these plants have been in operation since the 1960s and few are fairly new. Part of this evaluation study is to estimate the desalinated water cost in Libyan Dinar and US dollar per cubic metre and comparing them to other regions in the world. Cost of desalinated water at four industrial sites has been assisted and the summary is presented in this work. The cost varies, but in some locations, the cost of water is as low as LD 0.5/m^3 ($US 0.40).

Keywords: Economic analysis; Desalinated water cost; Multi-stage flashing (MSF); Multi-effect evaporation (MEE); Multi-effect evaporation with thermal vapor compression (MEE/MEE-TVC); Libyan oil and gas sector; LPI

1. Introduction

The availability of water for chemical or petrochemical industries are essentially important in steam production, make-up water, washing water, water direct contact cooling, or process feed water. Lack of natural sources of water with certain requirements in Libya is considered a major challenge in front of any industrial development project especially in the Libyan oil and gas production and processing. However, the only possible option to obtain the high quality water in a remote area is seawater or brackish desalination. Desalination plants may utilize the low or wasted thermal sources such as low-grade steam or waste heat recovery within the processing facility. For instance, seven thermal desalination units in area II in the Mersa El Brega chemical complex operated by Sirte Oil Company (SOC) have been thermally integrated with the two urea plants within the complex. The excess steam generated during the thermal recovery within the urea production process is utilized as a heating source for the desalination units.

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Presented at the Conference on Desalination for the Environment: Clean Water and Energy 11–15 May 2014, Limassol, Cyprus

Since the mid-1960s in Libya, the most applied water desalination process for oil and gas industrial purpose are thermal desalination processes. Non-thermal processes such as reverse osmosis (RO) or elector dialysis were less used; nevertheless, these technologies are widely used when water demand is small such as in oil and gas fields in the desert, operators camps, hospitals, hotels, food production and processing facilities, and other domestic applications. However, the thermal processes are able to produce huge amounts of distillate water with high purity (Salinit ≤ 10 ppm) and at reasonable costs. Distillate water can be easily made drinkable by adding a number of minerals, chemicals, and pH adjustment additives. Distillate water produced at thermal units (e.g. multi-stage flashing [MSF]) can be directly used as well as with minimum further additional post-treatment in an industrial unit such as boiler. There are several alternatives of thermal technologies available such as multi-stage flashing with recycle brine or once through (MSF-BR/MSF-OT) and multi-effect evaporator without and with thermal vapor compression (MEE/MEE-TVC). These technologies are adopted in Libyan and the first desalination unit (MSF) was installed in 1964 in the area I of the Mersa El Brega chemical complex. Details on these technologies can be found elsewhere [1,2].

Temperature has a great effect on the performance desalination process in thermal units. MEE plants operate at lower temperatures (63–75℃) than MSF plants (100–110℃), reducing operational problems resulting from scaling and corrosion. This low-temperature evaporation is achieved by implementing vacuum at different level within the unit. MEE pumping and electrical power requirements are typically 33% lower than MSF, and seawater intake water requirements may be 50% lower than a similarly sized MSF. However, all these factors, and more others, should be examined when selecting a suitable technology for future utilization. One of the important factors of thermal desalination unit is the performance ratio (PR), which is the ratio of kg of water produced to 1 kg of steam consumed. For example, in a typical MEE unit, each kilogram of input steam can be used to produce 8 kg of product water (Table 1).

2. Desalination economics

The objective of this work is to present elements of desalination economics evaluation in order to estimate unit product costs, $\$/m^3$ of water, based on a convenient method for estimating the cost of desalted water, is illustrated. Moreover, the analysis explains why the estimation of accurate water cost is quite a difficult task. The economic analysis is concerning the desalination plants used to produce water only (e.g. not dual purpose plants to generate electricity and produce water. A calculation of the unit product cost depends on the process capacity, site characteristics, and design features. System capacity specifics sizes for various process equipment and pumping units. Factors that determine the cost of water production include both fixed and operating charges as shown Eq. (1). The detailed components of these costs are listed in below (Fig. 1). Costs are usually calculated on annual or monthly basis.

$$\text{Unit Product Cost} = \text{Fixed Costs} + \text{Operating Costs} \tag{1}$$

2.1. Fixed costs

Fixed charges that must be included in the total cost of producing water from a desalination process are predominantly the result of capital costs, consisting mainly of amortization and interest to recover the installed cost of the plant. For example, the capital cost of the plant is a fixed cost to be paid annually for repayment of the loan required for financing the project. The amount of these payments will depend on the total cost of the installation, the applicable interest rate, and amortization period. The capital recovery factor (f_r) is given as follows:

$$f_r = r + \frac{r}{(1+r)^N + 1} \tag{2}$$

where r is the interest rate. The second term in the equation $(r/(1+r)N-1)$ is the sinking fund depreciation factor and N is the amortization period which is equal to the number of annual payments. The capital recovery factor f_r is calculated for selected values of r and N as given in Table 1.

The sinking fund depreciation takes into account the timing of returned money by including the interest rate. If the installed cost for the plant is $\$I$, then the annual capital cost would be $I \times f_r$ ($/y). The other fixed costs are due to charges for property taxes and insurance. These are usually in the order of 1 or 2% of the installed cost of the plant.

- The plant availability factor (AF) influences water cost in rigorous estimate. Forced and planned outage of a desalination unit for maintenance and repair reduces its availability for production. Fixed charges are paid whether the plant is operating or out of operation. Design considerations

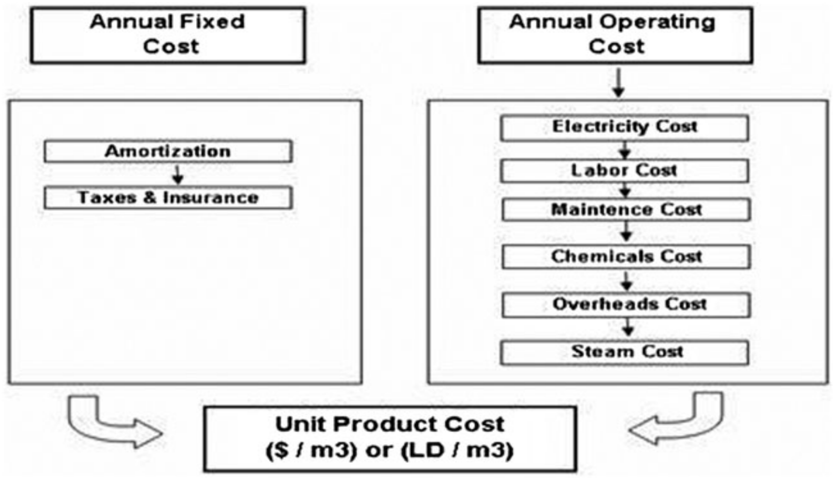

Fig. 1. Breakdown of the unit product cost of desalinated water.

Table 1
Capital recovery factor (f_r)

	Interest rate, *r* % per year		
N (Year)	5	7.5	10
10	0.128	0.146	0.163
20	0.08	0.100	0.117

such as selection of materials of construction, degree of sparing of pumps and control valves, reliability of off-site facilities, and selection of superior equipment components influence the availability of the plant. An example illustrating the influence of AF and capacity factor (CF) on the annual fixed cost (AFC) is shown in Table 2. The plant has a capacity of 454.6 m^3/d and the plant total AFC equals to \$67,500/y (AFC = Interest & Amortization + Tax & Insurance). For more comparison, plant factor is the combined factor of availability and CF (PF = AF × CF). This factor has a great effect on the specific annul fixed cost as shown in Table 2, and whenever the plant availability or its production reduced, the unit product cost for capital cost would be increased. Plant factor of 90–95% is considered typical and healthy values on year basis.

$$\text{Specific annual fixed cost} = \text{AFC}/(\text{plant capacity} \times \text{AF} \times \text{CF}) \quad (3)$$

- The capital investment cost of installed plant constitutes of delivered cost plus the cost of erection in a location has to be considered in which the installed cost of a plant is multiplied by a location factor >1.0 that depends on the plant location (a location factor of space 1.0 is set for the eastern USA coast).
- Installed plant cost can be estimated by the specific installed cost (SIC) of thermal desalination units and the plant capacity. Generally speaking, SICs for an MEE plant is lower than for an MSF plant by 10–20% (Table 3).

2.2. Operating costs

2.2.1. Fuel costs (steam costs)

Fuel costs makes up the greatest part of the total production cost of water. The cost of fuel per product water varies directly with price of fuel and inversely with PR. Low PR means high-steam consumption and hence high-fuel consumption. The international prices for fuels are subject to change at any time, although, fuel prices are quite constant on an yearly basis in Libya, e.g. fuel oil ≈ \$28/ton [8]. As far as the exhausted thermal sources of energy can be used such as saturation steam, this source energy will save substantial part of costs. The steam cost can vary from \$2 to 3.5/ton [4] and as far as the steam loses its kinetic energy and heat energy is left, the steam becomes much cheaper (superheated steam cost > \$3/ton < saturation steam cost). The recovered steam from waste streams will be a free source of energy.

2.2.2. Power cost

Power consumption depends on the size of the plant and mode of distillation. MED plants consume less power than MSF plants that require higher power consumption for recycled pumps; however, MED plants do not. On the other hand, MEE-TVC units consume much less power than MEE-MVC units; the latter are power-intensive process. In fact, power may cost less especially on site generation. Generally speaking, the estimation purpose power cost can be taken as \$0.04–0.09/kWh [1] and average value can be taken as \$0.037/kWh [3] for Libya. Estimated energy requirements of three type desalination plants are shown in Table 4.

2.2.3. Labor costs

The payroll of the plant will include mainly permanent staff for operation, routine maintenance, and administration. Labor costs include desalination plant's operators and management staff. The figure can be varied from one place to another and for local or overseas labor.

2.2.4. Chemical treatment costs

All desalination plants are usually designed to operate on an anti-scale program to prevent scale formation along with periodic acid cleaning. Multi-effect evaporator (MEE) units consume less chemicals since they use less feed seawater compared with MSF plants. Table 5 shows typical costs of a number of chemicals used in desalination unit.

2.2.5. Maintenance costs

Including spare parts and manpower for non-routine maintenance are usually estimated on the basis of the labor experience, plant size and age, and location. Generally speaking, this can be considered as a fixed cost amounting yearly to 1–1.5% of the total installed cost of the medium plant size; see Table 6.

2.2.6. Overhead costs

These figures are used in order to fulfill any money flow shortage for a project. If this item is not available for calculations, it can be taken as 100% of labor costs [14].

2.2.7. Factors affecting the product cost

- Salinity and quality of feed water:
    - Lower feed salinity allows for higher conversion rates.

Table 2
Specific AFC vs. plant factor

	Case 1	Case 2/Case 3	Case 4
Capacity factor	1.0	1.0/0.9	0.9
Availability factor	1.0	0.9/1.0	0.9
Plant factor	1.0	0.9	0.81
Specific annual fixed cost	\$0.406/m^3	\$0.452/m^3	\$0.502/m^3
Percent change	0.00%	11.33%	22.64%

Table 3
SIC of desalination units

	Year	MSF	MEE or MEE-TVC	MEE-MVC	RO
SIC, \$/(m^3/d) [3]	Typical	1,481			500
SIC, \$/(m^3/d) [1]	1996–1997		900–1,600		1,000
SIC, \$/(m^3/d) [1]	1992–1993	1,500–2,269	1,562–2,100		1,665
SIC, \$/(m^3/d) [4]	Med. 1990s		900–1,600		800–1,200
SIC, \$/(m^3/d) [4]	Early 2000	1,100–1,600	900–1,250		700–1,000
SIC, \$/(m^3/d) [5]	?	1,000–2,000		2,500–3,000	800–1,250
SIC, \$/(m^3/d) [6]	Recent estimation	1,050–3,150			
SIC, \$/(m^3/d) [7]	1990s	1,800	900		800
SIC, \$/(m^3/d) [8]	2003		1,450–1,700		
SIC, \$/(m^3/d) [9]	?	2,000	1,500		1,300
SIC, \$/(m^3/d) [10]	1980s	Average 1,500	Average 1,300		
SIC, \$/(m^3/d) [10]	1990s	Average 1,700	Average 1,600		

Table 4
Energy requirements comparison between MSF, MEE, and RO

	MSF [12]	MEE [4]	RO	
Possible desalination unit size (m^3/d)	≈60,000	?	≈ 24,000 [12]	? [4]
Energy consumption (kWh/m^3)	4–6	1–2.5	5–7	4–7
Electrical equivalent for thermal energy (kWh/m^3)	8–18	4–7	–	–
Total equivalent energy consumption (kWh/m^3)	12–24	5–9.5	5–7	4–7

Table 5
Estimation of chemical cost and dosing rates [1]

Chemical	Unit cost ($/kg of chemicals)	Typical dosing rate (kg chemical/kg water)	Specific cost ($/$m^3$ water)
Sulfuric acid	0.504	2.42E-5	0.0122
Antiscalant	0.701	1.4E-5	0.0098

  - Dosing rate of anti-scalant chemicals are less when the feed has low salinity.
  - Downtime related to scaling is considerably reduced at lower salinity.
- Plant capacity: Larger plant capacity reduces the capital cost for unit product, although the increase in the plant capacity implies higher overall capital.
- Site conditions: Installation of new units as an addition to existing sites would eliminate cost associated with facilities for feed water intake, brine disposal, and feed water pre-treatment.
- Qualified manpower: Availability of qualified operators, engineers, and management would result in higher plant availability, production capacity, and lower down time caused usually by faulty devices trips.
- Energy cost: Availability of inexpensive sources of fuel, electric power, and heating steam has a strong impact on the unit product cost.
- Plant life and amortization: Increase in plant life reduces the product cost.

3. Typical unit product cost

In general, production costs tend to be in the range of \$1–4/m^3 [1,6] depending on technology applied, size of the unit, capital cost, operating costs, and other factors. Lower figures can be achieved through the usage of cheaper source of energy. Typical ranges of unit product cost of seawater desalination:

(1) Large plants \$0.75–\$1.5/m^3 [1,3,11]
(2) Small plants \$2.00–\$3.0/m^3 [1,3,11]

The definition of large or small plants depends on the mode of desalination process used and production capacity. Distillation-mode desalination plants such as MSF plants are usually large-sized plants (2,000–20,000 m^3/d), whereas MED or MED-TVC plants are medium/small-sized units (≤5,000 m^3/d). The economic benefit of large-scale plants is clearly evident from Table 7. In Libya, the estimation of the cost of one cubic metre of desalted water is around \$1–3/m^3 [8–10].

4. Water production cost at Tubruk oil refinery

The total production cost of distillate water is the result of *capital (fixed) cost* and *operating cost*. Basic cost data were obtained from the refinery. Missing data have been estimated using commercially realistic costs or cost factors as well as relying on some past experience in the field of desalination. The following calculations include the two desalination units (unit 1 and unit 2) and finally show the cost in terms of \$/m^3 water produced by the plant, so that a comparison with standard costs can be made. Location factor[1] for Libya of 1.7 is employed. The units are manufactured by a British company.

4.1. Installed cost

The design capacity of each unit is 375 m^3/d. The installed cost of a single unit is \$758,712 and the delivered cost of each unit is \$758,712/1.7 = \$446,301. Thus, the fixed investment per unit product is \$446,301/(375 m^3/d) = \$1,190/m^3. This is in agreement with the

[1]Source of information: international cost engineering counsel.

standard cost of medium size MEE desalination plants, which quotes \$1,100–\$1,200/m^3.

4.1.1. Interest and amortization charges

To calculate the capital recovery factor f_r, we shall consider a simple loan where the whole investment amount is reimbursed to bank or investors by 15 constant annuities with interest rate = 7.5% per year. Thus, for $N = 15$ and $r = 0.075$, $f_r = 0.113$, and the interest and amortization costs are \$758 ,712 × 0.113 = \$85,734.5/y. Introducing availability factors, we obtain the investment and amortization charges for each unit individually: unit 1 (plant factor is 55%) is \$1.139/m^3 and unit 2 (plant factor is 45%) is \$1.394/m^3.

4.1.2. Taxes and insurance charges

Property taxes and insurances are charged yearly as a fraction of installed cost. These are assumed to be at 3% per year, i.e. \$758,712 × 0.03= \$22,761/y. Unit 1 total specific charge is \$0.302/m^3 and for unit 2 is \$0.370/m^3.

The Capital (fixed) charges:

Unit 1: \$1.139/m^3 + \$0.302/m^3 = \$1.441/m^3.

Unit 2: \$1.394/m^3 + \$0.370/m^3 = \$1.764/m^3.

4.2. Operating costs

4.2.1. Ejector steam (fuel consumption)

Fuel consumption per day is 6.00 tons fuel/day typical to produce the required heating steam. According to the costs data sheet, the fuel used costs \$50/ton. For each unit, we obtain that unit 1 is \$0.44/m^3 water and unit 2 is \$0.44/m^3 × (0.45/0.55) = \$0.36/m^3 water.

4.2.2. Power cost

The total power consumed by the plant is given as 56 kW. This may be distributed as follows:

Boiler	at 13% = 7.28 kW.
Seawater pump	at 36% = 20.16 kW.
Desalination plant	at 44% = 24.64 kW.
Lighting misc.	at 7% = 3.920 kW.
	Total = 56 kW.

Cost of power is \$0.004/kWh and therefore, the cost of power per m^3 produced water is \$0.0144/m^3 (both units), or the average for each unit is \$0.072/m^3.

4.2.3. Cost of repairs and maintenance

This cost is usually taken as 1% of the delivered cost (fixed investment) of a plant per year, i.e. \$446,301 × 0.01/y = \$4,463/y. The cost of repairs and maintenance given to us by the refinery is \$4,408/y. The two figures are quite close. Thus, the cost of maintenance per m^3 product water is \$0.032/m^3 (for each unit).

4.2.4. Labor cost

This is fixed since the payroll of the plant will include mainly permanent staff for operation and routine maintenance. However, this cost increases if the plant AF drops. The cost of labor per m^3 product water for each of the desalination units is \$0.173/m^3 distillate water.

4.2.5. Chemical cost

The units are using different type of chemicals such as anti-scale, corrosion inhibitor, pH adjustment additives, and acid for cleaning when it is needed. This is estimated at \$0.15/m^3 for both units. Therefore, it is \$0.0825/m^3 for plant 1 while it is \$0.0675/m^3 for unit 2.

4.3. Total cost (\$/m^3)

The real average production cost = (\$2.241/m^3 + \$2.469/m^3)/2 = \$2.355/m^3. The production cost estimation for a single unit operating at design capacity can be estimated as follows:

(1) *Fixed Cost:* \$1.441/m^3 × 0.55 = \$0.793/m^3.
(2) *Operating Costs.*

- Fuel cost: \$0.80/m^3. (PR = 75% PR$_{design}$).
- Labor cost: \$0.173/m^3.
- Power cost: \$0.144/m^3.
- Maintenance cost: \$0.032/m^3.
- Chemical cost: \$0.150/m^3.
- *The water cost at normal operation condition* = \$2.1/m^3.

The results of these calculations show that the product cost is slightly high (\$2.355/m^3) in comparison with production cost at design capacity. As mentioned before, the refinery operates the two units at reduced capacities in order to achieve the desired water demand, where as a single unit operating at full capacity is sufficient to fulfill this demand. The refinery philosophy on this is that one unit in operation is required at a time and to maintain both units in good operation condition, they have to operate each unit every month or so. Also, due to remote location of this

Table 6
Typical maintenance cost factor for thermal units [13]

Production capacity (m^3/d)	Installed plant cost (IEC)	Maintenance cost factor, % of IEC	Annual maintenance Cost
454.6	$200,000	4	$8,000
4,546	$750,000	1.5	$11,250

Table 7
Comparison of water produced by RO and MSF units [3]

Technology	Production capacity, m^3/d	Fixed charges, $/m^3	Operating charges, $/m^3	Water cost, $/m^3
RO	1,454.75	1	0.75	1.75
	4,546.1	0.75	0.7	1.45
	22,730.4	0.5	0.7	1.2
MSF	1,454.75	1.5	1.05	2.55
	4,546.1	1	1	2
	22,730.4	0.5	0.85	1.35

refinery, water redundant unit is required in case one unit is out of operation due to forced shutdown maintenance.

5. Water desalination cost at Azzawyia oil refinery

The desalination units at this refinery are operated by Azzawyia refining company. A total of seven multi-stage evaporation type desalination units have been installed in refinery. Five of them are multi-stage flash once through (MSF-OT) and the other two are MEE-TVC. They are presently operating to provide fresh water for the refinery and other process units. The MSF-OT units are useful at their final operation days when we have done this study as they are going to be decommissioned soon and scrapped. They are very old and their status is not in good condition; therefore, they are not included in the economic

Table 8
Detailed water cost components for Azzawyia unit 7

Unit	**7 (MEE-TVC)**			
Designed capacity	**1000**	m^3/d		
Year	-			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	152,986.07	152,986.07	12.19	11.39
2-Taxes and Insurance	3,886.57	3,886.57	0.31	0.29
Total capital costs =	156,872.64	156,872.64	12.50	11.68
Operating Costs (OC)				
1-Steam cost	1,037,610.00	1,123,290.00	82.66	83.60
2-Power cost	2,529.79	2,772.48	0.20	0.21
3-R&M cost	26,049.13	26,049.13	2.08	1.94
4-Labour cost	3,576.09	3,576.09	0.28	0.27
5-Chemical cost	11,424.07	12,520.00	0.91	0.93
6-Overhead costs	3,576.09	3,576.09	0.28	0.27
7-Seawater cost	13,637.16	14,945.40	1.09	1.11
Total operating costs =	**1,098,402.33**	**1,186,729.19**	**87.50**	**88.32**
Total costs =	**1,255,274.97**	**1,343,601.84**	**100.00**	**100.00**
Unit product cost LD/m^3	3.81	5.39		
Unit product cost $/m^3	2.87	4.05		

analysis. The refinery actually depends on MEE-TVC units for reliable water supply. Economic evaluation and cost of water produced have been estimated based on information and data of unit number 7 (MEE-TVC). The MSF units are manufactured by a Germany company while the MEE-TVC units are manufactured by a French company.

The objective of this section is to present elements desalination cost. The presentations outline components of fixed cost and operating cost. Calculations of the unit product cost depend on the process capacity, site characteristics, and design features. System capacity specifies sizes for various process equipment and pumping units. In this calculation, the official exchange rate used is \$1 = 1.33 L.D. An Excel spreadsheet is prepared in order to save time and to obtain accurate results. The calculations are based on the assumptions listed below and will be used as a reference:

(1) The operation life of each unit is 20 years with 10% interest rate on borrowed capital for the calculation of capital recovery factor.
(2) The cost of repair and maintenance including replacement of parts (e.g. pumps, pipes, etc.) is taken as 2% of installed cost of plant per year
(3) The overhead cost is taken as 100% of labor cost. This is a fixed cost that includes administration, training, and indirect costs.
(4) The cost of pumping, chemical treatment, and filtration of intake seawater is taken to be 0.005 LD/Ton as given by SOC.
(5) The cost of chemicals is estimated from their real consumption considering plant availability.
(6) One option for unit cost of product water is presented. The option includes both fixed and operating costs.

5.1. Unit 7 (MEE-TVC type)

This unit appears to be good in operation during evaluation period. As the reported data and questioners show, the unit worked with AF was greater than 90%. The product cost mainly consist of two items: steam cost (energy) and interest, and amortization costs. The strange thing is that other items have disappeared in their effect on product cost. Table 8 gives the cost details for the unit if it operates according to the design condition with full production capacity and according to the actual production capacity. The water production cost according to design operation condition would be \$2.865/m^3 while the real water cost was \$4.05/m^3. It is noticed that the amounts of water produced by the units are only to meet the demands regardless of the cost consequences. The cost of water produced by each unit should be determined on individual basis rather than collectively as noticed at the refinery records; otherwise one would think that the units have equal operating costs.

6. Water production cost at Ras-Lanuf chemical complex

The Ras-Lanuf chemical complex has five desalination units all of multi-stage flash with bribe recirculation (MSF-BR) type to provide fresh water for drinking, domestic, and industrial purposes through desalination of seawater. The units have the same production capacity of 6,000 m^3 distillate water per day if top brine temperature (TBT) = 90˚C and 8,400 m^3/d if TBT = 115˚C. The units are of the large capacity type and when operating together, they are capable of providing 42,000 (TBT = 115˚C)–30,000 (TBT = 90˚C) m^3 of fresh water per day. However, the present daily demand for water at Ras-Lanuf is not more than 12,000 m^3/d (e.g. less that 40% of total design capacity), and for this reason only two units are now being operated at the same time. The whole five units are manufactured by an Italian company.

The following calculations are for the five desalination units (Unit A, Unit B, Unit C, Unit D, and Unit E) as shown in Tables 9–13, based on actual data available at Ras-Lanuf for the five units. The cost is finally given in terms of LD/m^3 or \$/m^3 water produced for the units for comparison with costs based at design conditions. An Excel spreadsheet is prepared in order to save time and to obtain accurate results. The calculations are based on the assumptions shown before in Azzawyia oil refinery cost analysis. Unit A is the oldest unit and most problematic one. This unit appears to be out of operation most of the time during the evaluation period as reported by Ras-Lanuf, with only 1,188 working hours at availability of 13.5%. This directly reflects on the water cost illustrated in Table 7; design operation would be \$0.784/m^3 to \$2.392/m^3. Unit B and C are also old units but they are in good condition and have better operation reliability, which results with acceptable water cost of around \$1/m^3. Unit D and E are also in good condition and are fairly new, and their water cost is around\$1/m^3.

7. Water production cost at Mersa Brega petrochemical complex

The Mersa Brega petrochemical complex of Sirte Oil Co. consists of a number of oil, gas processing,

Table 9
Detailed water cost components for Ras-Lanuf Unit A

Unit	**A (MSF-BR)**			
Designed capacity	**6,000.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	404,278.96	404,278.96	19.62	46.78
2-Taxes and Insurance	15,832.53	15,832.53	0.77	1.83
Total capital costs =	**420,111.49**	**420,111.49**	**20.38**	**48.61**
Operating Costs (OC)				
1-Steam cost	1,027,095.55	150,723.44	49.84	17.44
2-Power cost	196,058.88	29,462.40	9.51	3.41
3-R&M cost	68,837.09	9,042.00	3.34	1.05
4-Labour cost	119,151.59	119,151.59	5.78	13.79
5-Chemical cost	45,357.38	6,816.00	2.20	0.79
6-Overhead costs	119,151.59	119,151.59	5.78	13.79
7-Seawater cost	65,221.20	9,801.00	3.16	1.13
Total operating costs =	**1,640,873.30**	**444,148.03**	**79.62**	**51.39**
Total costs =	**2,060,984.79**	**864,259.52**	**100.00**	**100.00**
Unit product cost LD/m^3	1.043	3.182		
Unit product cost \$/m^3	0.784	2.392		

Table 10
Detailed water cost components for Ras-Lanuf Unit B

Unit	**B (MSF-BR)**			
Designed capacity	**6,000.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	404,278.96	404,278.96	21.25	27.96
2-Taxes and Insurance	15,832.53	15,832.53	0.83	1.09
Total capital costs =	**420,111.49**	**420,111.49**	**22.09**	**29.05**
Operating Costs (OC)				
1-Steam cost	1,027,095.55	610,601.26	54.00	42.23
2-Power cost	33,203.52	22,772.40	1.75	1.57
3-R&M cost	68,837.09	75,699.00	3.62	5.23
4-Labour cost	119,151.59	119,151.59	6.26	8.24
5-Chemical cost	49,345.71	33,843.40	2.59	2.34
6-Overhead costs	119,151.59	119,151.59	6.26	8.24
7-Seawater cost	65,221.20	44,731.50	3.43	3.09
Total operating costs =	**1,482,006.26**	**1,025,950.76**	**77.91**	**70.95**
Total costs =	**1,902,117.76**	**1,446,062.25**	**100.00**	**100.00**
Unit product cost LD/m^3	0.962	1.298		
Unit product cost \$/m^3	0.724	0.976		

Table 11
Detailed water cost components for Ras-Lanuf Unit C

Unit	**C (MSF-BR)**			
Designed capacity	**6,000.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	404,278.96	404,278.96	21.34	32.84
2-Taxes and Insurance	15,832.53	15,832.53	0.84	1.29
Total capital costs =	**420,111.49**	**420,111.49**	**22.17**	**34.12**
Operating Costs (OC)				
1-Steam cost	1,027,095.55	453,303.87	54.21	36.82
2-Power cost	33,203.52	18,963.00	1.75	1.54
3-R&M cost	68,837.09	39,251.00	3.63	3.19
4-Labour cost	119,151.59	119,151.59	6.29	9.68
5-Chemical cost	41,930.74	23,947.24	2.21	1.95
6-Overhead costs	119,151.59	119,151.59	6.29	9.68
7-Seawater cost	65,221.20	37,248.75	3.44	3.03
Total operating costs =	**1,474,591.30**	**811,017.05**	**77.83**	**65.88**
Total costs =	**1,894,702.79**	**1,231,128.55**	**100.00**	**100.00**
Unit product cost LD/m^3	0.959	1.478		
Unit product cost \$/m^3	0.721	1.111		

Table 12
Detailed water cost components for Ras-Lanuf Unit D

Unit	**D (MSF-BR)**			
Designed capacity	**6,000.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	481,192.68	481,192.68	24.07	27.74
2-Taxes and Insurance	18,844.66	18,844.66	0.94	1.09
Total capital costs =	**500,037.34**	**500,037.34**	**25.01**	**28.83**
Operating Costs (OC)				
1-Steam cost	1,027,095.55	612,498.10	51.37	35.31
2-Power cost	33,203.52	24,481.80	1.66	1.41
3-R&M cost	81,933.29	271,600.00	4.10	15.66
4-Labour cost	119,151.59	119,151.59	5.96	6.87
5-Chemical cost	53,556.27	39,488.40	2.68	2.28
6-Overhead costs	119,151.59	119,151.59	5.96	6.87
7-Seawater cost	65,221.20	48,089.25	3.26	2.77
Total operating costs =	**1,499,313.02**	**1,234,460.73**	**74.99**	**71.17**
Total costs =	**1,999,350.36**	**1,734,498.07**	**100.00**	**100.00**
Unit product cost LD/m^3	1.012	1.563		
Unit product cost \$/m^3	0.761	1.175		

Table 13
Detailed water cost components for Ras-Lanuf Unit E

Unit	**E (MSF-BR)**			
Designed capacity	**6,000.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	772,297.03	772,297.03	33.01	35.73
2-Taxes and Insurance	30,245.00	30,245.00	1.29	1.40
Total capital costs =	**802,542.03**	**802,542.03**	**34.31**	**37.13**
Operating Costs (OC)				
1-Steam cost	1,027,095.55	868,297.58	43.90	40.17
2-Power cost	33,203.52	32,785.20	1.42	1.52
3-R&M cost	131,500.00	114,250.00	5.62	5.29
4-Labour cost	119,151.59	119,151.59	5.09	5.51
5-Chemical cost	41,502.44	40,979.56	1.77	1.90
6-Overhead costs	119,151.59	119,151.59	5.09	5.51
7-Seawater cost	65,221.20	64,399.50	2.79	2.98
Total operating costs =	**1,536,825.90**	**1,359,015.04**	**65.69**	**62.87**
Total costs =	**2,339,367.93**	**2,161,557.07**	**100.00**	**100.00**
Unit product cost LD/m^3	1.184	1.264		
Unit product cost \$/m^3	0.890	0.950		

Table 14
Detailed water cost components for Mersa Brega unit 7 Area II

Unit	**7 (MSF-BR)**			
Designed capacity	**2,400.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	131,725.45	131,725.45	29.98	27.07
2-Taxes and Insurance	33,643.59	33,643.59	7.66	6.91
Total capital costs =	**165,369.04**	**165,369.04**	**37.64**	**33.98**
Operating Costs (OC)				
1-Steam cost	152,754.30	160,794.00	34.76	33.04
2-Power cost	24,215.00	22,290.35	5.51	4.58
3-R&M cost	22,429.06	69,473.00	5.10	14.27
4-Labour cost	9,636.00	9,636.00	2.19	1.98
5-Chemical cost	24,172.00	24,172.00	5.50	4.97
6-Overhead costs	9,636.00	9,636.00	2.19	1.98
7-Seawater cost	31,187.59	25,327.93	7.10	5.20
Total operating costs =	**274,029.95**	**321,329.28**	**62.36**	**66.02**
Total costs =	**439,398.99**	**486,698.32**	**100.00**	**100.00**
Unit product cost LD/m^3	**0.556**	**0.758**		
Unit product cost \$/m^3	**0.418**	**0.570**		

Table 15
Detailed water cost components for Mersa Brega unit 6 Area I

Unit	**6 (MEE-TVC)**			
Designed capacity	**1,000.00**	m^3/d		
Year	**-**			
	Economic summary			
	(LD/yr)		**Percentage of cost share**	
Capital Costs (FC)	**Design**	**Operation**	**Design (%)**	**Operation (%)**
1-Interst and Amortization	88,635.27	88,635.27	36.30	30.44
2-Taxes and Insurance	22,638.06	22,638.06	9.27	7.77
Total capital costs =	**111,273.33**	**111,273.33**	**45.57**	**38.22**
Operating Costs (OC)				
1-Steam cost	76,123.00	76,123.00	31.17	26.14
2-Power cost	6,823.32	4,247.41	0.13	1.46
3-R&M cost	15,092.04	57,348.00	6.18	19.70
4-Labour cost	15,108.00	15,108.00	6.19	5.19
5-Chemical cost	2,821.00	2,821.00	1.16	0.97
6-Overhead costs	15,108.00	15,108.00	6.19	5.19
7-Seawater cost	8,343.12	9,143.49	3.42	3.14
Total operating costs =	**139,418.48**	**179,898.90**	**54.43**	**61.78**
Total costs =	**250,691.81**	**291,172.23**	**100.00**	**100.00**
Unit product cost LD/m^3	**0.804**	**1.503**		
Unit product cost \$/m^3	**0.605**	**1.130**		

and petrochemical plants. They are served by 12 desalination units of multiple effect evaporation types to provide fresh water for drinking and industrial uses through desalination of seawater. We note the following from these units:

- There are nine desalination units of multi-flash type (MSF-BR). The other three units are thermal vapor compression type (MEE-TVC).
- The petrochemical plants area consists of seven units served by seven MSF desalination units of similar capacity (2,400 m^3/d). These desalination units are located in an area called area II.
- The oil and gas processing plants consists of five desalination units; three of them are MEE-TVC type of the same capacity (946 m^3/d), where as the other two are MSF type of different capacities (757 and 1,892 m^3/d). These are located in area I.
- The first and oldest MSF unit in Libyan oil sector was installed in 1964 for the oil and gas plant at that time. Surprisingly, this unit is still yielding 757 m^3/d of distillate water after many years in operation.
- Commissioning of the desalination units started in 1977 through 1989, apparently due to rapid expansion in oil and gas processing and thereby created big demand on fresh water.

The following calculations are for the two desalination units (unit 7 in area II and unit 6 in area I) as shown in Tables 14 and 15, based on data available at Mersa Brega for the two units. The cost is finally given in terms of \$/m^3 water produced for the two units so that a comparison with design operation costs can be made. The designed and actual water costs for MSF-BR unit 7 in area II are \$0.416/m3 and \$0.57/m^3, respectively. For unit 6 in the area I, these numbers are \$0.605/m^3 and \$1.130/m^3, respectively. The low water cost observed in this complex is due to the heat integration utilization in which the heating steam is provided from the urea plants. Good maintenance and operation programs and experienced and skilled engineers/operators are another contributing factor in this low costs. The units in area I are manufactured by American companies, while area II is manufactured by Germany companies.

8. Comparison desalinated water product cost

The following Table 16 describes the unit product cost for different processes and different capacities. It should be known that a large size plant is cheaper to run than a multiplicity of smaller units. However, the small units provide flexibility in the water production and allow available spare units in case the demand increased or the normal units become out of service due to unforeseen problems.

Table 16
Unit product cost for thermal desalination processes [2]

	Unit cost, \$/m^3	Production capacity, m^3/d
Multi-effect evaporators with mechanical vapor compression, MEE-MVC		
MEE-MVC example 1	1.51	1,000
MEE-MVC example 2	0.89	750
MEE-MVC example 3	2.48	4,000
MEE-MVC example 4	3.22	500
MEE-MVC example 5	2.43	4,546
Multi-effect evaporators with thermal vapor compression, MEE-TVC		
MEE-TVC example 1	2.34	Not available
MEE-TVC example 2	1.55	22,166
MEE-TVC example 3 [15]	0.95	31,822
This study—Tubrok Oil Refinery	*2.355 average*	*750 (two units)*
This study—Azzawyia Oil Refinery	*4.05*	*2,000 (two units)*
This study—Mersa Brega complex	*1.13*	*1,000 (one unit)*
Multi-effect evaporators, MEE		
MEE example 1	1.95	Not available
MEE example 2	1.08	37,850
MEE example 3	1.24	22,730
MEE example 4	1.397	22,730
Multi-stage flashing process, MSF		
MSF example 1 [15]	1.04	31,822
MSF example 2 [15]	0.84	57,000
MSF example 3	1.84	Not available
MSF example 4	1.25	37,850
MSF example 5	1.61	45,460
MSF example 6	1.498	45,460
*This study—*Ras-Lanuf *complex*	*1.3196 average*	*30,000 (five units)*
This study—Mersa Brega complex	*0.57*	*16,800 (seven units)*

Table 16 compares the desalinated water cost in those selected units in the Libyan oil sector vs. the published water cost elsewhere around the world. The standard cost of desalinated water varies, but it is generally around \$1–2/m^3 for almost all type of thermal desalination units and the cost goes up (>\$2/m^3) for small capacity units. MEE and MEE-TVC have close cost range due to the similarity of the process concept, although TVC should be more cost efficient due to lower energy consumption. However, the cost range is between \$1 and 2.5/m^3 while the range of MSF unit becomes around \$1.5/m^3. MEE-MVC has a desalinated water cost range of \$1–3/m^3, which is quite high compared with non-mechanical compressed system such as MEE and MEE-TVC. This is mainly due to high power consumption, the lower production capacity compared with non-mechanical compressed systems and also to higher maintenance cost due to the nature of the operation of the system in which the compressor internals are subject to fouling and scale formation on them. This is why this technology is not employed as much as other technologies especially in the Libyan oil sector.

For MEE-TVC water costs, the desalinated water cost in Tubrok oil refinery and Mersa Brega complex seem to be quite close to the published costs for MEE-TVC units, except the desalinated units of Azzawyia oil refinery that seem to be quite high compared to Tubrok or Mersa Brega units. This is due to high investment costs of these units compared to other units and to high-energy costs. For MSF units, the water cost for both Ras-Lanuf and Mersa Brega are very acceptable compared to the international water cost. The Mersa Brega cost in area II is \$0.57/m^3, which is much lower than the reported international water cost due to the heat integration between the urea plants and water desalination units.

9. Conclusion

(1) Detailed and systematic economic evaluation of operating desalination plants in Libyan oil sectors to estimate the desalinated water cost has been presented by highlighting the most effluence factors of the water cost.

(2) The economic evaluation study has covered desalination plants located in four oil and gas facilities along Libyan costal line on Mediterranean Sea.
(3) Two desalination technologies have been found widely applied in Libyan oil sectors and they are multi-stage flashing with recycle brine or once through (MSF-BR/MSF-OT) and multi-effect evaporator without and with thermal vapor compression (MEE/MEE-TVC).
(4) The desalinated water cost of MSF plants at a design operating condition was varying from \$0.41 to 0.89/m^3 while the real condition cost vary from \$0.57 to 1.0/m^3, with the except of one plant in which the cost was quite high, \$2.40/m^3. The lowest cost units were those in the Mersa Brega complex. The desalinated water cost for some units was found as low as \$0.57/m^3 due to the fact that these units are energy integrated with urea chemical plants at the site.
(5) For most of the MSF plants, the major share of cost was energy (heating steam from 30 to 40%) and same percentage range for capital cost. The repair and maintenance was from 5 to 14% and it was always high for old units.
(6) The desalinated water cost of MEE plants at design operating conditions varied from \$0.60 to 2.865/m^3, while the real condition costs vary from \$1.13 to 4.05/m^3. The high real costs are due to low-plant production demand and availability as well as high energy costs.
(7) For most of the MEE plants, the major share of cost was energy (heating steam from 25 to 35%, except in one unit were high ~80%). The second influential factor was the capital cost with an average value of 35%. The repair and maintenance was from 5 to 20%.
(8) It can be concluded that water cost should be low or close to those reported internationally, however, Libyan desalination units are considered unique due to the fact that they are using low-energy grade (low-energy cost) or recovered waste heat energy (heat integration). Flexible and low governmental charges were usually given. The availability of intensive experience in thermal desalination plants and experienced operators make the operation of desalination plants more efficient and even with very old units or troubled ones.
(9) It is very likely that the Libyan oil sector, and may be other major Libyan sectors, would adopt the utilization of thermal desalination plants like MSF and MEE. Non-thermal process such as reverse osmosis might find more acceptance in small applications where the energy utilization is not available/feasible, or the water consumption is not huge.

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