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Preliminary techno-economics assessment of developed desalination/salt recovery facility based on membrane and thermal techniques

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ABSTRACT

Successful management of desalination plants should incorporate integrated processing of seawater feed and brines. An integrated 20,000 m^3/d zero desalination discharge (ZDD) facility, merging desalination and salt recovery, has been developed incorporating both membrane and thermal processes. Chemically pretreated seawater has been directed to nanofiltration (NF) separator for almost complete removal of divalent salts. NF brine loaded with magnesium has received further concentration by multiple effect evaporator and the reject obtained from reverse osmosis (RO) processing of NF permeate has been further directed to state-of-the-art ion selective electrodialysis (ED) to enable downstream production of magnesium and sodium salts. The material balance of the developed integrated desalination/salt recovery ZDD facility enabled total water recovery of about 70%. The average product salinity after mixing approached 74 mg/l. The total amount of recovered raw magnesium, calcium and sodium chloride salts were 215, 47 and 754 ton/year, respectively. The financial indicators revealed that the total capital and annual operating and maintenance costs (O&M) as well as unit cost were 99.5 M$, 13 M$/year and 2.48 $/$m^3$, respectively. The total annual revenues of water and chemicals approached 27.5 M$/year. Thus, the initial net profit was about 11.1 M$/year. About 0.98 $/$m^3$ could be realized via selling of recovered salts. These results confirm the promising features of the developed desalination/salt recovery ZDD facility. It is worth mentioning that with different possible financial risk factors, such as market fluctuations and taxes, the net profit would decrease to approach 7.7 M$/year and 3.1 M$/year, respectively.

Keywords: Desalination; Salt recovery; Membrane; Thermal; Techno-economics; Revenues

1. Introduction

The main drawbacks of brackish and seawater desalination include the burden on the environment due to the disposal of high concentration brines and also the high operating and production costs of these non-conventional potable water production schemes [1,2]. Partial softening of hardness calling ions will enable trouble-free operation and extended MF and efficient utilization of accessible energy [3,4].

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Integrating the concept of partial or complete softening with those selective salt separations would reveal considerable revenue from commercialization of the produced salts. The other impact on operating costs, MF and energy saving are also fully recognized [5–7].

Chemical softening using lime, sodium carbonate and/or sodium hydroxide has been practiced successfully for seawater pretreatment and combined separation of Ca and Mg in numerous plants [8–10]. Also, the intensive efforts regarding membrane softening by nanofiltration (NF) modules confirm cost-effective application of this technology for most divalent ions (80–90%) and significant fraction of monovalent ions (30–40%) [6]. It should be emphasized that NF permeate is almost deprived of hardness elements, other divalent pollutants, soluble organics and manifests lower osmotic pressure. Consequently, the downstream of desalting facility (thermal or reverse osmosis [RO] membrane) will not be subjected to scaling problems, flux decline and would manifest energy utilization [11–14]. The NF brine could be subjected to chemical treatment to eliminate significant fraction of calcium salts and leaving most of magnesium salts to be recovered in the subsequent cost-effective processes [5,15,16].

The current developments in electrodialysis (ED), ion exchange membranes and cell design enable successful fractionation of RO brines into rich magnesium stream (diluate) and sodium chloride concentrated stream (reject). The diluate permits direct recovery of magnesium hydroxide using further treatment with sodium hydroxide. The ED concentrate, characterized by high monovalent concentration (up to 20%), could be directed to thermal concentration [17–20]. Other salt recovery practices have been reported by the United States Bureau of Reclamation (USBR) regarding treatment of concentrate from desalination plants [21,22]. The issues of zero desalination discharge (ZDD) have been the subject of numerous international endeavors [18].

In this paper, the concepts pertinent to technically feasible 20,000 m^3/d desalination/salt recovery facility will be described. Moreover, windows of opportunities pertinent to salt recovery revenues will be highlighted against annual capital and total O&M costs.

2. Approach and methodology

The analysis of the developed ZDD facility depends on the outcome of previous endeavors, indicators achieved by screening and analysis of worldwide endeavors, in addition to experimental results presented in different contributions [8,23]. A medium-scale ZDD facility (desalination/salt recovery) incorporating state-of-the-art membrane separation processes, including MF, NF, RO and ED, in addition to thermal separation modules including multiple effect evaporator (MED) and evaporator crystallizer with product water production capacity of 20,000 m^3/d, has been developed as a model for techno-economic analysis. The selection of the capacity and adopted technology features state-of-the-art ZDD facility was recommended for future implementation. It is worth mentioning that the environmental benefits associated with salt recovery have not been addressed in the current analysis.

2.1. Basis of cost estimation

Capital and operating costs for seawater desalting facility are estimated using “WT Cost II” software. WT Cost II© is a visual basic software developed by the Bureau of Reclamation and Moch Associates dealing with water treatment costs.

Basis of cost estimation adopted are as follows:

(1) Direct capital cost includes the cost of land, major and auxiliary process equipment and construction costs. Freight and insurance, construction overheads and contingency costs are part of the indirect capital costs [24].
(2) Annual operating costs are after plant commissioning and during plant operation including chemicals, energy, wages, plant maintenance, expenditures, etc. [24].
(3) Plant life is based on 30 years [25].
(4) “Evaporator/crystallizer” (brine concentrator unit) costs are based on USBR report (2006) [18].
(5) Drying bed costs are based on Desalting handbook for planners (2003) [26].
(6) All capital costs have been updated to 2013 using ENR-CCI cost index.
(7) The revenues are estimated according to reported market prices of raw salts [27,28].
(8) 0.5% of direct capital cost and 2% of O&M costs are accounted for auxiliary items.
(9) Financial analysis does not account for the capital and operating costs of the marine outfall which would have to be incorporated in the base case.

3. The integrated desalination/salt recovery facility

The developed integrated desalination/salt recovery ZDD facility (for water production capacity 20,000 m^3/d) is shown in Fig. 1. The figure presents the flow and total dissolved solids (TDS) of each

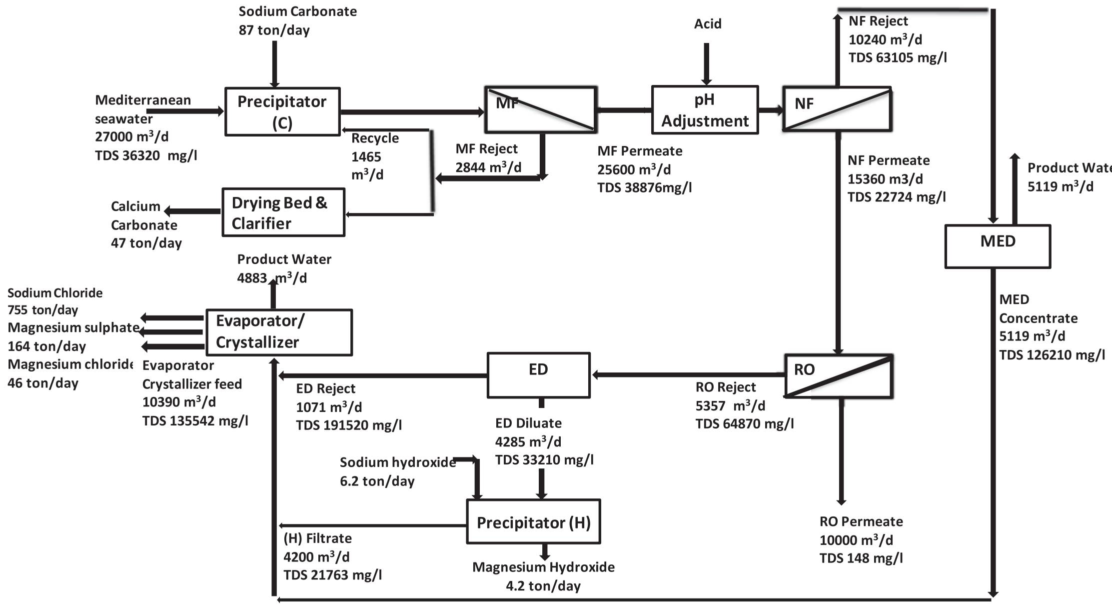

Fig. 1. Schematic flow diagram of the integrated desalination/salt recovery ZDD facility.

stream, as well as salt recovery from different units based on material balance.

The ZDD facility includes integrated membrane system comprising MF/NF/RO/ED in addition to two thermal processes (MED and evaporation crystallization). Feed water stream is subjected to calcium carbonate precipitation using sodium carbonate at pH 9.2 (Precipitator C). The precipitate is consisted mainly of calcium ions accompanied with some magnesium ions. Other water contaminants such as barium, strontium, silica, etc. will be precipitated as well. Bottom of the precipitation tank with 0.5% solids concentration will be directed to MF unit. The MF permeate (about 90% of feed flow) with almost no suspended solids will be fed to NF unit after pH adjustment, while 50% of the MF reject will be directed to a drying bed equipped with a clarifier and the other portion is recycled to the precipitator. The brine stream from NF is directed towards MED process where recovery reaches 50% as NF removes almost scaling ions. The MED concentrate stream is further processed using "evaporator/crystallizer" unit in which most of the produced salts are magnesium-rich salts. The permeate stream from NF unit is directed to RO as NF eliminates about 40% of the salt load directed to RO unit. The brine stream from RO unit is further desalinated using ED with monovalent ion selective membrane. The reject stream from ED, where NaCl concentration is up to 20%, is further processed to the pre-mentioned evaporator/crystallizer. The diluate stream is processed using precipitation with sodium hydroxide at pH 11 (Precipitator H) and the filtrate is directed to the "evaporator/crystallizer". About 4 m^3/d of filtered seawater will be added to the overall product water (20,000 m^3/d) to adjust TDS up to 300 mg/l.

The performance indicators and main technical specifications of the selected units are depicted in Tables 1 and 2 [6,18,29–33].

4. Financial indicators

Capital and O&M costs, as well as unit costs for the developed integrated desalination/salt recovery facility are shown in Table 3, while Table 4 depicts the breakdown of capital and O&M costs for the selected units. The financial indicators revealed that the total capital, annual O&M and unit costs were 99.5 M$, 13 M$/year and 2.48 $/m^3, respectively. It is observed that the cost ratios of the major units represented by membrane and thermal modules to the overall capital are 38.6% and 59.4%, respectively. The corresponding values for O&M costs are 41.9% and 15.6%, respectively. The estimated unit cost (2.48 $/m^3) is considered apparently high, which may be attributed to the involvement of salt recovery unit processes.

5. Revenues generated by salts production

5.1. Impact of salt recovery

The amounts of salts produced by different units, estimated selling price for raw chemicals and salts

Table 1
Typical performance indicators for the separation processes of the developed desalination/salt recovery ZDD facility [6,18,29–33]

	Removal efficiency (%)							
	Precipitation		Membrane system				Thermal system	
Item	(C)	(H)	MF	NF	RO	ED	Evaporator/crystallizer	MED
Ca^{2+}	95.5	95	–	83	99.4			
Mg^{2+}	14	95	–	85	99.4			
Na^{+}	–	–	–	35	99.4		95	
Cl^{-}	–	–	–	35	99.4			
Water recovery* (%)			90	60–65	50–65		47–50	50
Diluate feed ratio (%)						80		
Power consumption (kWh/m^3)			0.1–0.5	1.1–1.9	3–5.5	2–4	20–40	1.5–7

*From seawater and RO brine.

Table 2
Main technical specifications of selected processes

Item	Specifications
MF	Element flow: 38 l/s; membrane life: 10 years
NF	Element flow: 30 m^3/d, pressure drop 207 Kpa, feed pressure 4,820 kpa; no. of trains/no. of elements per vessel: 10/7, pump: 163 hp
RO	Element flow: 23 m^3/d, pressure drop 138 Kpa, feed pressure 3,100 kpa; no. of trains/no. of elements per vessel: 5/7, pump: 311 hp
Monovalent ion selective ED	NaCl concentration in the reject stream is up to 20% (3-fold concentration). Area/membrane pair is 0.85 m^2, current density 30 amps/m^2, current efficiency 0.86
MED	Single purpose MED, power cycle used: CCGT
Precipitator (C) and (H)	Bed depth: 5 m, retention time: 180 min, G-rating: 70%
Drying bed	I m^2 is required for each 14.7 kg of precipitate mass

and total annual revenues are depicted in Table 5. The total desalted water generated by RO, MED and "evaporator/crystallizer" unit are about 10,000, 5,119 and 4,883 m^3/d, respectively. Raw $CaCO_3$ generated after chemical precipitation approaches 47 ton/d. Magnesium salts obtained from the "evaporator/crystallizer" unit were 164 ton/d $MgSO_4{\cdot}7H_2O$, 46 kg/d $MgCl_2$, while 4.2 ton/d of $Mg(OH)_2$ was generated from ED diluate. The net daily produced raw sodium chloride approaches 755 ton/d. It is expected that calcium, magnesium and sodium recovery from the developed desalination/salt recovery facility reached 90, 72 and 93%, respectively. It is also shown that the total annual revenues from magnesium salts approach 26% of the total revenues as compared to 54% of sodium salts revenues.

The total annual revenues approach is 27.5 M $/year and the estimated net annual profit is about 11.1 M$/year. In addition, the expected revenues and net profit for selling produced water and salts are 4.16 and 1.68 $/$m^3$, respectively, per 1 m^3 of product water.

5.2. Comparison with conventional desalination

"WT cost II" software was also used for a cost estimation of conventional RO (base case) desalination plant with traditional pretreatment without salt recovery. It was indicated that the total capital, O&M and unit costs are about 19.78 M$, 2.73 M$/year and 0.41–0.53 $/$m^3$, respectively. Thus, there is a marginal profit if the water is sold in 0.7 $/$m^3$as assumed in the revenues estimation, as shown in Table 5.

The O&M costs in case of salt recovery exceeds the base case by about 10.34 M$/year. On the other hand, the expected revenues from produced chemicals approaches 22.8 M$/year. Thus, it is clear that the apparent gross profit, without considering taxes, exceeds by about 12.5 M$/year in case of salt

Table 3
Capital, O&M and unit costs of the developed desalination/salt recovery ZDD facility

Process	Capital cost (1,000 $)			Annual O&M cost (1,000 $)	Total annual (1,000 $)	Unit cost ($/m^3)
	Direct	Total	Annualized			
1. MF	4,453	6,412.32	213.7	881	1,094.7	0.166
2. NF	4,328	6,232	207.7	951	1,158.3	0.173
3. RO	3,295	4,744.8	158.2	789	947.2	0.144
4. MED	11,625	16,740	558	1,670	2,228	0.338
5. ED	16,750	24,120	804	2,805	3,609	0.468
6. Evaporator/crystallizer	32,702.1	39,242.5	1,308.1	370	1,678.1	0.254
7. Drying bed	297.1	356.5	11.9		11.9	0.002
8. Precipitator (C)	673	969.1	32.3	3,747		0.528
9. Precipitator (H)	178.8	250.8	8.6	1,609.4	1,617.9	0.245
10. Others	371.5	445.8	14.86	256.5	271.3	0.041
Integrated facility	74,673.7	99,520	3,302.3	13,074.1	16,396.5	2.48

Table 4
Break down of capital and O&M costs of selected processes

Unit	Cost (1,000 $)							
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
	NF		RO		ED		MED	
Membrane	411		463					
Membrane replacement		68		74		163		
Cartridge filters	105	11	61	13		22		
Trains	176		198					
Membrane cleaning	66	83	66					
Chemicals				89		1		20
Steam								1,191
Pumps	543	16	648	14				
Electricity		450		339		2,501		168
Labor		183		176		24		
Miscellaneous	3,027	140	1860	85		84		291
Total	**4,328**	**951**	**3,295**	**789**	**16,750**	**2,805**	**11,625**	**1,670**

Table 5
Revenues of produced salts and water from the developed desalination/salt recovery ZDD facility

Material	Annual production (1,000 ton)	Selling price* ($/ton) [27,28]	Annual sales (1,000 $)
$CaCO_3$	15.5	50	776
$MgSO_4 \cdot 7H_2O$	54.1	100	5,412
$Mg(OH)_2$	1.3	250	330
$MgCl_2$	15.2	90	1,366
NaCl	249.2	60	14,949
Water	6,600	0.7	4,620
Total revenues			27,470
Net			
Profit			11,073

*Price for raw chemicals.

recovery. About 0.98 $/m^3 could be realized via selling of recovered salts. It is worth mentioning that the base case doesn't include the capital and operating cost of marine outfall and seawater intake, neither the environmental impact. Calculation of the revenues was built on the conservative (pessimistic, rather than optimistic).

5.3. Sensitivity analysis

Further endeavors were required to assess different risk factors that may adversely affect the revenues of the integrated desalination/salt recovery facility.

5.3.1. Market fluctuations

Decreasing selling price of about 15% due to market fluctuations would decrease the annual revenues and annual profit to 24.1 M$/year and 7.7 M$/year, respectively. Also, the depicted revenues and net profit for selling produced water and salts would decrease to reach 3.64 $/m^3 and 1.16 $/m^3, respectively, per 1 m^3 of product water.

5.3.2. Taxes

Further decrease of profit may be expected due to taxes of about 35%. The annual revenues and the annual profit would decrease to 19.5 M$/year and 3.1 M$/year, respectively, while the depicted revenues and net profit for selling produced water and salts would decrease to reach 3 $/m^3 and 0.47 $/m^3, respectively, per 1 m^3 of product water.

6. Conclusions

An integrated 20,000 m^3/d desalination/salt recovery ZDD facility has been developed incorporating four membrane processes, namely, MF, NF, RO and ED, in addition to two thermal processes comprising MED and evaporation/crystallization. Amounts of raw calcium carbonate, magnesium (sulphate, chloride and hydroxide) and sodium chloride salts produced from the developed facility approach 47, 215 and 755 ton/d, respectively. It is depicted that calcium, magnesium and sodium recovery from the developed desalination/salt recovery facility reach 90, 72 and 93%, respectively.

The financial indicators revealed that the total capital and annual operating and O&M as well as unit cost were 99.5 M$, 13 M$/year and 2.48 $/m^3, respectively. The total annual revenues approached 27.5 M $/year. Thus, the initial net profit was about 11.1 M $/year. The apparent gross profit without considering taxes is higher by about 12.5 M$/year in the case including salt recovery than the base case. About 0.98 $/m^3 could be realized via selling of recovered salts. It is worth mentioning that with different possible financial risk factors, such as market fluctuations and taxes, the net profit would decrease to approach 7.7 and 3.1 M$/year, respectively.

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