AN INNOVATIVE MEMBRANE BASED ZERO DISCHARGE SYSTEM FOR MANAGEMENT OF AGRICULTURAL DRAINAGE WATER (ADW) AND SALT RECOVERY

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Abstract - Implementing a successful zero discharge system is constrained by numerous technological challenges and economic constrains necessitating development of innovative cost-effective solutions and interventions. This paper introduces an innovative integration of separation technologies using high pressure membrane scheme and electrically assisted adsorption separation units. The agricultural drainage water" ADW" could be treated as well as avail high-quality water and commercial salts using this innovative scheme. Three innovative features have been incorporated within the general arrangement of this innovative zero liquid discharge system. The first intervention is related to the introduced electrically assisted adsorption/ion exchange units for eliminating heavy metal species typically present in ADW. Second, improvement represents a sound solution for improving the quality of the brine generated by RO stage to suit the requirements of the second high pressure RO module. Problems of scaling will be greatly minimized by interposing these adsorption/ion exchange units between the two stage RO units. Dealing with the generated brine from the second membrane unit with a remarkable solar assisted engineered artificial wet-land maintains production of commercial salts with minimal adverse environmental impact. The estimated cost is $0.242/m3 of produced water.

Keywords - Adsorption, Electro Assisted, Reverse Osmosis Membrane, Wastewater, ZLD.

I. INTRODUCTION

Reverse osmosis concentrates (ROC), a by-product of the reverse osmosis (RO) process, include a high concentration of dissolved organics, persistent organic pollutants, inorganics, and other contaminants. Careful control and safe disposal of ROC is crucial in water reclamation processes Liang et al. (2021). The phrase "zero liquid discharge" (ZLD) refers to a treatment method in which the facility does not discharge any liquid effluent into surface waterways, therefore eliminating all treatment-related pollution. Aside from this benefit, a ZLD process makes optimal use of wastewater treatment, recycling, and reuse, which contributes to water conservation by lowering the quantity of fresh water consumed [1].

ZLD systems are gaining popularity as feasible wastewater treatment/water management alternatives for industrial and agricultural drainage wastewater. The treatment, purification, and recycling of wastewater are all part of these wastewater treatment systems. The ZLD approach completely eliminates liquid discharge from industry, hence minimizing and eliminating environmental issues while also meeting regulatory disposal requirements [2].

Because of its very effective removal capabilities, RO has recently become a popular alternative to traditional water treatment procedures [3]. Concerns about potential environmental issues have grown as RO desalination has progressed. The RO method has a fundamental drawback in that it produces and discharges a large volume of concentrate [4-5]. The RO concentrate generated as a by-product in a RO plant converts all the pollutants rejected by RO into a stream with a concentration 4-7 times that of RO feed [6].

When using the desalination technology, the issue of brine disposal is a serious environmental concern. Brine disposal technologies include deep well injection, land disposal, surface water discharge, the Sal-proc process, mechanical/thermal evaporation, and evaporation ponds [7]. Because such reverse osmosis concentrate (ROC) may contain large concentrations of rejected compounds such as refractory chemicals and medicines in addition to personal care products (PPCPs), inappropriate discharge of such ROC may pose a risk to human and environmental health (Ahmed, 2001). The large-scale discharge of RO concentrate depletes water supplies and harms the ecosystem [8]. As a result, administering a ROC therapy before to release is required to avoid any potential health risks to the environment and live things [9-10].

Ion exchange and adsorption are two typical wastewater treatment technologies. Heavy metals such as Pb2+, Cr3+, Fe3+, Cu2+, and ammonia are removed via ion exchange procedures, which employ zeolites and resins [11]. Heavy metals and a range of organic contaminants, such as benzene, phenolic compounds, carbon tetrachloride, nitrophenol, acid dyes, and p-dichlorobenzene, are removed from wastewaters using adsorption procedures that use activated carbon, peat, iron oxide, kaolin, and fly ash [12]. In hard water solutions, the presence of soluble Ca (II) and Mg (II) salts has resulted in unsuitable behaviour for drinking, irrigation, and industrial

purposes. Ionic pollutants might create problems in cooling and heating systems, steam generation, and manufacturing. Due to high calcium and magnesium concentrations, scaling in the form of carbonate, sulphate, or phosphate precipitates has choked pipes and heat exchangers [13]. As a result, the need for water with a low hardness level has arisen in critical occupational areas for businesses such as leather processing [14].

Solar evaporation ponds for desalination brine are a good solution for disposing of reject brine from inland desalination facilities in arid and semi-arid settings due to the abundance of solar energy [15]. Solar evaporation is the process of water evaporating from the sun. Solar ponds increase the project's worth not only in terms of desalination process economics, but also in terms of environmental desalination process economics [16- 19].

To create high quality water from agricultural wastewater, a hybrid RO – adsorption – evaporating pond method was devised in this research. The suggested hybrid system is expected to produce a 95% water recovery rate. The technical aspects and economic indicators of the designed scheme were estimated using simulation.

II. MATERIALS AND METHODS

The main goal of this work is to establish ZLD system for treating drainage water contaminated with industrial effluents polluted with heavy metals.

To achieve this goal the following objectives are set forth:

- ZLD system conceptual design.
- Technical system analysis of ZLD based on RO and adsorption systems.
- Identification of cost indicators of the system.
- Addressing environmental considerations related to ZLD.

To achieve these objectives the following methodology will be applied:

Development of ZLD system for treating water from industrial complex dealing with engineering industries with water characterized by high TDS and contamination with heavy metal from electroplating activities.

Identification of the main technical specifications of the process and process equipment based on well-established technologies.

Utilization Lewa Plus Software to identify the main features of the RO and ion exchange systems applied Fig. (1) presented a screen shot of the mentioned software.

Identification of the cost indicators for the proposed system based on the software as well as updated published data using the pre-mentioned software.
Presenting environmental aspects related to the proposed ZLD.

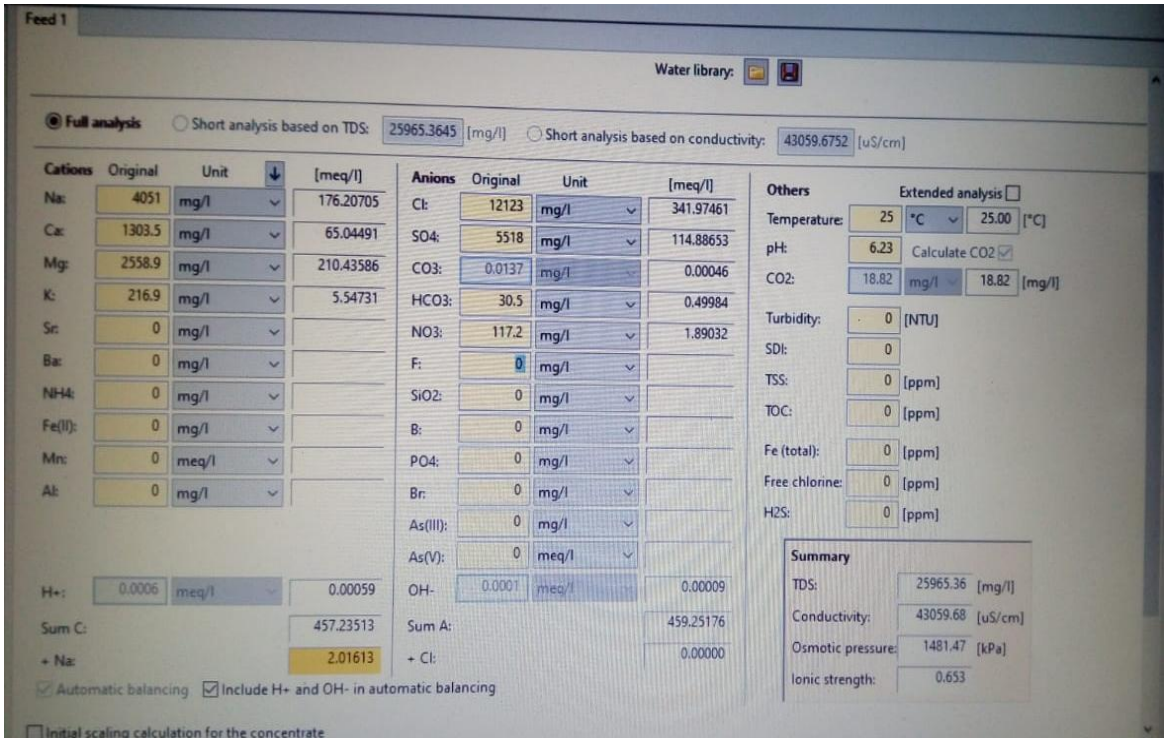


Fig. (1): A Screen Shot of the Applied Software.

A. Proposed ZLD Conceptual Design Features

As Shown in Figure (2) the conceptual design of the proposed ZLD system comprises the following main units:

- Reverse osmosis to recover 80-90% of the water.
- Ion exchange de-alkalinization to remove part of the Ca and Mg as well as heavy metals. The resin regeneration effluent is further treated to remove heavy metals by adsorption. Electrically assisted chemical desorption could be applied to enhance recovery of heavy metals.
- Reverse osmosis to recover more water from ion exchange treatment unit.
- Wastewater effluents resulting from ion exchange, and final reverse osmosis concentrate are directed to solar evaporation pond, after adjustment of pH to recover salts. Salts are frequently harvested from the ponds for use as raw materials for pure chemicals.

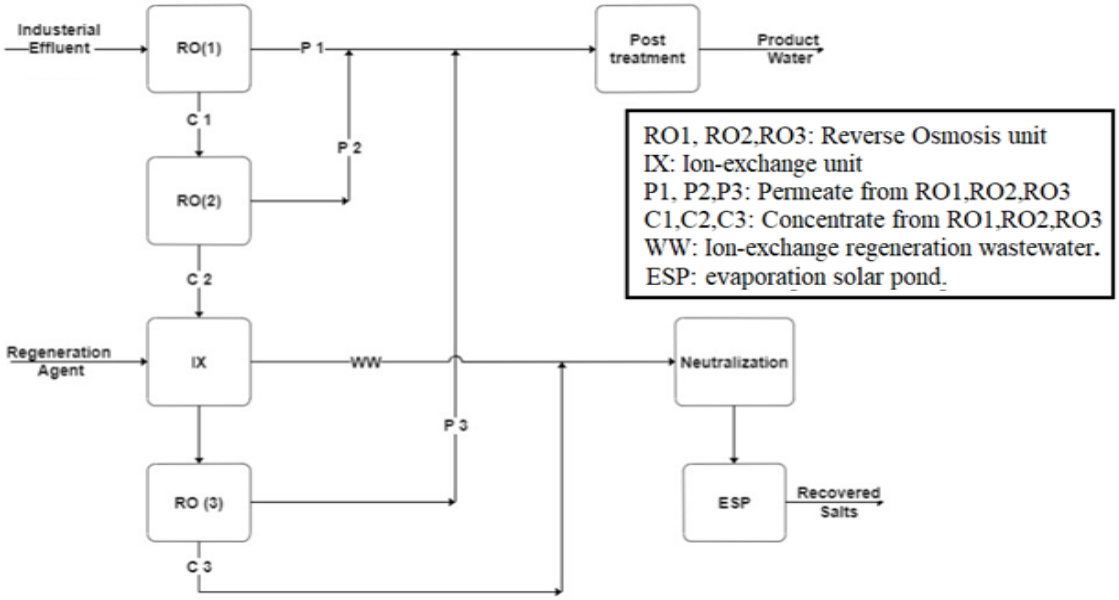


Fig. (2): A schematic block flow diagram for the proposed ZLD system.

III. RESULTS AND DISCUSSION

A. Conceptual ZLD system case study

The proposed ZLD system is intended to provide fresh water for an industrial complex in Egypt from an agricultural drain contaminated with heavy metals. The composition of raw water is typically illustrated in Table (1).

Item	Composition	Item	Composition
Na (mg/l)	586	Cl (mg/l)	980
Ca (mg/l)	27	SO4 (mg/l)	235
Mg (mg/l)	142	CO3 (mg/l)	1.8
K (mg/l)	27	HCO3 (mg/l)	366
TDS (mg/l)	2403	NO3 (mg/l)	38
Zn (mg/l)	1	CO2 (mg/l)	9.8
Cr (mg/l)	0.5	TDS (mg/l)	2403
Ni (mg/l)	0.5	pH	7.7

Table (1) Raw water composition

The ZLD proposed process flow diagram is schematically presented in Figure (3). The basis of design and basis technical characteristics of RO units are presented in Table (2). The basis of design and main characteristics of ion-exchange unit is presented in Table (3). Further, the basis of design and main technical characteristics of the solar pond are presented in Table (4). Table (5) summarizes the

compositions of the main streams of the system (please mention in brief how was it calculated, if possible). In a similar work, Bond et al. (2008) reported that incorporating a secondary RO to treat RO brines from inland desalination saved 58−75% of energy and 48−67% of treatment cost as compared to using only a brine concentrator followed by an evaporation pond.19,21 Notably, although the secondary RO largely reduced the volume of brine entering the brine concentrator, the capital/ operation cost of the brine concentrator remained a major contributor to the total treatment cost [20].MATH

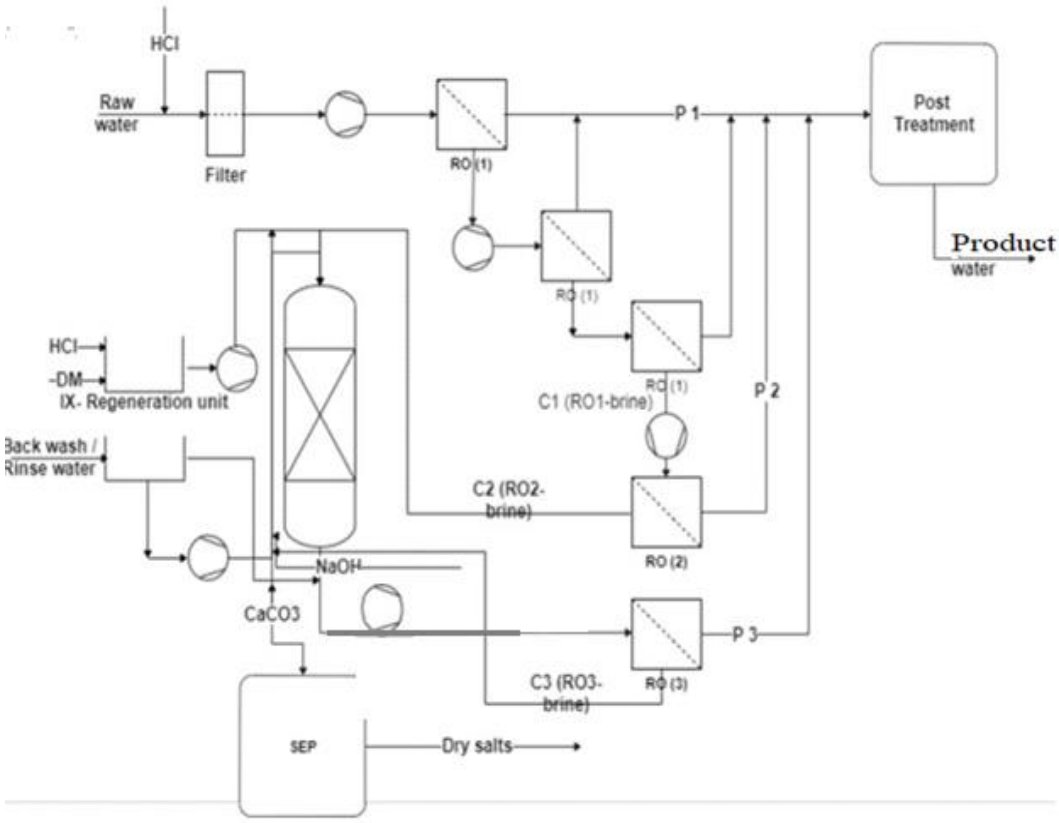


Fig. (3): A detailed Process flow diagram of the proposed ZLD system.

Item	Value		
	RO1	RO2	RO3
Permeate flow rate (m3/d)	10,000	794	286.8
Feed pressure (bar)	13	25.8	42.8
Booster pump pressure (bar)	1	----	---
Permeate recovery (%)	85	45	30
Feed pH	5.5	6	
Feed temperature 9°C)	25	25	25
Scale inhibitor dose (mg/l)	2	2	2
Acid (HCl) dose (as 100%) mg/l	188	53	12.3
Electricity (kWh/m3)	0.7	2.02	5.02
Membrane - Element type - Number of elements	 BWLP 400 34 SD 488	 BW LP 400 34 SD 42	 SWHR40034 15

Table (2): Main Technical Characteristics of RO units

Item	Value
Feed flow rate(m^3/d)	972
Net treated water product (m^3/d)	956
Treated water used for services (m^3/d)	16
Operating hours (h/d)	24
Regeneration parameters – Regenerant – Regenerant consumption (as 100%) (kg/d) – Demineralized water consumption (m^3/d) – Regeneration temperature (°C)	 HCl 4% 227.6 18 25
Plant dimensions – Resin type – Resin operating capacity (meq/l) – Specific flow rate (BV??./h) – Filter diameter (m) – Resin volume (L) – Resin bed depth (m) – Total cylindrical part length (m)	 CNP 80WS 2.03 14.46 1.2 2800 2.74 5.5
– Total pressure drop (bar)	1
– Regeneration time (h/d)	3
– Regeneration waste water quantity (m3/d)	35

Table (3): Basis of Design & Main technical characteristics of Ion-exchange unit

Item	Description	Value
Design basis	Average annual climatic conditions	
	Temperature (°C)	24
	Relative humidity (%)	60
	Wind speed (m/s)	3.5
	Solar Irradiation (W/m^2)	346
	Rain fall (mm/Y)	150
	Evaporation rate (mm/d)	33.1
	Elevation above sea	19 m
	Daily feed (m^3/d)	700
	TDS of feed water (mg/l)	42,000
Dimensions	Area (m^2)	140,000
	Total required area	190,000
	Pond Length (m)/ Pond width (m).	160/35
	Total height (m)	1.5
	No. of Ponds	25
Liner	HDPE (60 mil)	
	Geotextile	
	Clay (100 mm)	
	Graded liner (30 mm)	

Table (4): Main Technical Characteristics for the Solar Evaporation Pond

If you are using Word, use either the Microsoft Equation Editor or the MathType add-on

Item		RO1		RO2		IX		RO3	
	Raw water feed	P1	C1	P2	C2	TW	WW	P3	C3
Na(mg/l)	586	43.4	3672	151	6565	6565	2300	67.5	108100
Ca(mg/l)	27	0.71	176	2.5	318	292	3800	1.1	486
Mg (mg/l)	142	3.75	924	13.3	1670	1689	6000	6	2778
K (mg/l)	27	3	163	10.1	291	291	200	4.5	482.2
Cl (mg/l)	980	69.2	734.6	248	13266	13266	38500	121.3	22273
SO_4 (mg/l)	235	2.9	1555	11	2818	2816	2800	5.1	4693
CO_3 (mg/l)	1.8	--	0.12	--	0.2	--	0.7	---	0.7
HCO_3 (mg/l)	366	3.2	351	8.8	471	4	781.8	4.3	781.8
NO_3 (mg/l)	38	14.1	165	4.2	263	263	282.6	282.6	282.6
TDS (mg/l)	2403	141	19352	486	2576.2	25662	42394	209.7	42394
pH	7.7	4.34	6.22	46	6.23	6.23	6.23	4.4	6.5
HM (mg/l)	2	--	11.3	--	20.6	--	--	--	--

* Not including adsorbent regeneration effluents to be directed to HM recovery
P1,P2,P3 permeate from RO1, RO2, RO3
C1, C2, C3 concentrate from RO1, RO2, RO3

Table (5): Composition of the main streams of ZLD system

B. Cost Indicators for the Proposed ZLD System

Table (6) presents the estimated capital investment costs for ZLD system which amounts to $4.3 million. The major cost is that for reverse osmosis units which amounts to about $ 2.4 million. Ion exchange/adsorption unit capital investment is about $326,000 while solar evaporation ponds investment amounts to $1.93 million. The high investment required for solar evaporation pond is attributed to large area requirements and expensive liner required for wetted areas of the pond.

While, Vergili, et al. (2012) has proposed ZLD processes included various combinations of ultrafiltration (UF), loose nanofiltration (NF1), tight nanofiltration (NF2) and reverse osmosis (RO). The technological and economic performance of four different scenarios (UF/NF2 (S (I)), NF1/NF2 (S (II)), NF1/RO (S (III)) and UF/NF2/RO (S (IV))), each followed by membrane distillation (MD. The last two scenarios, those including RO, provided the best effluent quality at the end of the pressure-driven membrane filtration process. The unit treatment costs of the scenarios were 1.37, 1.38, 2.16 and 2.01 $/m3 of influent for S (I), S (II), S (III) and S (IV), respectively, with return periods of 0.87, 0.91, 2.07 and 1.51 years. The best technological and economic performance was estimated for S (I) and S (II), as indicated by the B/C ratios 3.58 and 3.55, respectively [21].

Item	Capital $1000		
I. RO units			
	RO1	RO2	RO3
RO train with pressure vessel, membrane elements and filters.	794.1	78.4	60
High pressure pumps	516.7	53.4	42
Post treatment unit	68.3	7.0	4
Piping	175.5	18.4	15
Membrane cleaning unit	121	12.5	7
Electrical system	87.8	9.1	6
Instrumentation and control	87.8	9.1	15
Contingency	195	20.2	15
Sub. total	2046.2	208.1	155
Total RO units	2409.3		
II. Ion Exchange/adsorption unit			
Resin vessels	120		
Resin	30		
Pumps	30		
Regeneration unit	50		
Piping	36		
Electrical	30		
Instrumental Control	30		
Sub total	326		
III. Solar Evaporation Pond			
Land ($ 2/m2)	380		
Earth works ($3/m2)	570		
Linear ($ 2.5/m2)	475		
Mechanical equipment	500		
Sub total	1,925		
Total	4297.2		

Table (6): Estimated Capital Investment for the Proposed ZLD System

Item	Bases	Annual Cost $1000/y
I. RO units		
Membrane replacement	Membrane lifetime 5y for RO1 and 3y for RO2, RO3,	46.8
Chemicals	HCl $300/t, scale inhibitor $1.8/kg, NaOH $300/t	332
Electricity	$0.07/kwh	231
Maintenance	3% of capital	72.3
Labour	12p @ $15,000/p.a	180
Sub Total 1		862.1
II. Ion-Exchange/adsorption unit		
Resin replacement	Resin lifetime 5y	6
Chemicals	HCl $300/t	75.6
Electricity	$ 0.07/Kwh (28000kwh/y)	2
Utilities	Dem. Water 2000 m3 2 $/m3	2
Maintenance	3% of capital	9.8
Labour	1 person @ 15000/p.a	15
Sub Total 2		110.4
III.Evaporation Solar Pond		
Maintenance	2% of capital	38.5
Fuel	10000 1/y @$1/L	10
Labour	2person@$10,000/p.a	20
Sub-total 3		68.5
Total Operating Cost		1041.0

Table (7): Estimated Annual Operating Cost for the Proposed ZLD

The annual operating cost of the proposed system is illustrated in Table (7). The total annual operating costs is estimated to be about $1.04 million per year. The RO unit cost represents about82.8% of the total operating cost, while ion exchange and evaporation pond cost represent 10.6% and 6.6% of the total operating cost, respectively.

The total production costs estimate for the system is presented in table (8) and amounts.

Item	Cost ($1000)/y
Operating Cost	1041.0
Amortization (at 4% interest rate, plant life 20y)	316.2
Total Annual Cost	1357.2

Table (8): Annual Cost of the Proposed ZLD system

The estimated water production cost taking into consideration the financial value of the recovered salts, is estimated to be $0.242/m2 as depicted in Table (9).

Item	Basis	Value $1000/y
Annual production cost		1357.2
Chemicals revenues	28t/d@$50/t, Load factor 0.9	468.1
Net Cost		889.1
Cost/m^3		0.242

Table (9): Estimated annual production cost and cost per m^3 produced water

In comparing the obtained results with previous work it was found for example that, In 2012, the Indian ZLD market was estimated to be worth $39 million, and between 2012 and 2017, 7% annual growth was predicted. Efficiency has been demonstrated to increase with the use of ambient air evaporators in ZLD systems for the treatment of tannery effluent Rajkumar et al. (2018). India's primary industries for ZLD use include the petrochemical, textile, brewery, power, and alcohol industries. However, to fully implement ZLD systems in India, there are issues that must be resolved about capital, land, and operating costs [23].

C. Environmental Aspects of the Proposed ZLD System

ZLD system offers many advantages related to environment. The advantages include recovery of high purity water from a polluted source at reasonable costs through applying environment friendly treatment technique based mainly on reverse osmosis which is considered the most economic well-established technique. The removal of heavy metals from wastewater resulting from ion exchange presents an additional advantage. The recovered small volume High concentrated wastewater could permit recovery of the heavy metals with high economic value and prevent heavy metals adverse effect if discharged to environment.

The use of solar evaporation though represents a negative environmental impact due to high land use, yet presents an appropriate resource recovery of economically valuable chemicals and prevent discharge of high salinity wastewater to environment.

Pretreatments that pollute the air, such acidification and degasification, release CO2 into the atmosphere. Additionally, excessive energy use results in significant greenhouse gas emissions. Additionally, CO2 is released during de-carbonation to prevent scaling and from ED applications used to concentrate RO brine from energy-intensive sources [24].

According to a California life-cycle study, greenhouse gas emissions would increase by 50% if brackish water reverse osmosis (BWRO) was used to recover water instead of importing it [25] . Implementing technologies like RO can reduce greenhouse gas emissions in terms of energy efficiency. Additionally, the use of low-grade or renewable energy through the integration of emerging membrane technologies into ZLD systems can help to lower greenhouse gas emissions [26].

IV. CONCLUSION

The proposed ZLD system could provide high quality water from the polluted source at a reasonable cost. The proposed system applied in the presented case study achieves 95% recovery of the raw feed water. Wastewater which amounts to only 5% of the feed water quality is directed to solar evaporation pond to recover chemicals of economic value. The estimated cost is $0.242/m3 of produced water.Better ZLD systems economics could be achieved through endeavors to reduce costs of system components and improving the quality of recovered chemicals to increase its financial value.

ACKNOWLEDGMENT

This work was financially supported by the Science and Technology Development Fund, Egypt, grant 8, project number 41563. Furthermore, all the work has been conducted inside the National Research Centre, Giza Egypt.

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