Design of an Oilfield Produced Wastewater Treatment Plant – UAE Perspective

Chandra Mouli R. Madhuranthakam, Archana Thomas, Zainab Akhter
Chemical Engineering Department,
Abu Dhabi University
Abu Dhabi, United Arab Emirates P.O.Box. 59911
chandra.mouli@adu.ac.ae
archana.susan.thomas@gmail.com
zainab_0@hotmail.com

Ali Elkamel[1,2]
1 - Chemical Engineering Department,
University of Waterloo,
Waterloo, Ontario, Canada
aelkamel@uwaterloo.ca
2 - Chemical Engineering Department,
Khalifa University of Science and Technology,
Abu Dhabi, United Arab Emirates, P.O.Box. 2533
ali.elkamel@ku.ac.ae

Abstract

During the extraction of crude oil from underground oil reservoir, around 3 to 10 barrels of water are generated for each barrel of oil which comes as a by-product of petroleum products that is known as produced water. Produced water is composed of toxic compounds which are known to cause irreversible damage to the environment. Treatment of produced water is necessary to enable its use in various industrial processes and even to meet regulations on toxic materials before discharging water into the environment. The goal of this article is to propose a method to treat and utilize the massive amount of produced water generated during oil extraction and to outline the means to achieve the proposed method. This paper also aims to develop, design and evaluate the possibility of treating produced water to bring down the toxicity level of the water such that it meets the cooling tower limit. In order to use produced water as make-up water, it is treated using sand filters, activated carbon filters, electrodialysis reversal and reverse osmosis units. This process facilitates treatment of about 1500m^3/hr of produced water in 15 hours.

Keywords
Produced water, cooling tower, electrodialysis reversal, reverse osmosis, refinery waste.

1. Introduction
Industrial wastewater is one of the primary sources of water pollution (SHI). Industrial wastewater is broadly classified by different industries and the level of contaminants present in them. Some common industries include iron and steel, textiles and leather, petrochemicals and refinery, microelectronics etc. (SHI). Industrial wastewater treatment is one of the most important processes in the world as many industries treat water to recycle it in their processes to save money and also to meet regulations on toxic materials before discharging water into the environment (Patwardhan, 2017). In a refinery, around 6 barrels of water are required for petroleum production and process facilities to produce 1 barrel of oil (Schultz, 2005). This is mainly utilized in cooling towers, as a feed to high-pressure boilers, as process water, like water for firefighting and potable water ; with the highest consumption

for cooling towers (Walker, 2013), (Wanf, 2014). Since the consumption of water is high, wastewater generated will also be high. Besides wastewater from processes, large quantities of water is generated as a by-product of petroleum products which has been reported to cause irreversible damage to the environment due to the presence of toxic components (Qomarudin & Kardena, 2015). Produced water (PW) is the water generated when extracting oil and gas from onshore and offshore wells. It accounts for the largest volume of the waste stream (up to 80%) in a typical oil and gas production operations. About 667 million metric tons (about 800 million m^3) of produced water was discharged offshore throughout the world according to statistics for the year 2003 (Neff, Lee, & DeBlois, 2011). The discharge volume has been increasing globally and there is a concern for the higher level of toxic materials in treated produced water compared to waterbodies it is discharged into.

1.1 Produced Water Constituents and its Composition

Typical constituents and its concentration range of produced water are listed below in Table 1 (Neff, Lee, & DeBlois, 2011).

Table 1. Concentration Range of Produced Water Components

Components	Concentration in ppm
Sodium	57526 - 61332
Potassium	1010
Calcium	14900 - 18097
Magnesium	1459 - 1700
Barium	0-19
Strontium	700 - 940
Iron dissolved	5 - 34
Boron	44 - 52
Aluminium	<0.5
Silicon	24 - 26
Lithium	18 - 22
Copper	<0.05
Manganese	0.32 - 0.34
Zinc	0.1 - 0.13
Chloride	120387 - 130958

Components	Concentration in ppm
Bromide	545 - 860
Nitrate	<5
Phosphate	<0.15
Bicarbonate	57 - 220
Carbon Dioxide	526 - 1235
Total Dissolved Solids	195353 - 212333
Dissolved Oxygen	0
Dissolved H_2S	32 - 123
Carbonate	0
Hydroxide	0
Total Oil and Grease (TOG)	2000
pH	5.9 - 6.12
SG @ 20 °C (kg/l)	1.083
Temperature°C	34.3

The impact of PW depends on the biological, physical, and chemical composition of the local environment from where the oil is being extracted. It is immediately discharged to the aquatic environment in the offshore extraction. Produced water contains a high amount of oil and grease, organic and inorganic, as well as dissolved and suspended constituents that are toxic in nature. Produced water contains inorganic and organic compounds that have high toxicity compared to crude oil. Discharge of such contaminated water into the freshwater bodies causes immense destruction to the aquatic environment and affect the agricultural resources. Moreover, produced water also contains biochemical oxygen demand (BOD) and chemical oxygen demand (COD) at a high level that is generated from fatty acids. BOD is the quantity of oxygen consumed by bacteria during decomposing organic matter and COD is the quantity of oxygen required to oxidize all organic matter into water and carbon dioxide. Aquatic destruction can also be due to the salinity level as it is higher in produced water than in sea water. In addition, produced water also contains heavy metals and naturally occurring radioactive material depending on the location of wells. Produced water contains lead that is poisonous which can result in anaemia, neurological defects, and kidney dysfunction. PW contains a high amount of total dissolved solids that increases the hardness of the water (Gazali, et al., 2017).

1.2 Reuse of Produced Water in Cooling Tower

As cooling tower has high water consumption in oil and gas industry, produced water can be used as make-up water for cooling towers. Every metric ton of crude oil produced per day circulates about 2 m^3 of water per hour through its cooling tower system. Reuse of produced water in cooling tower helps solve the problem of produced water disposal and thereby the environmental effects caused by it. Cooling Tower is a direct contact type heat exchanger in which warm water is cooled by mixing it with high velocity air. Warm water is introduced at the top of the cooling tower where it passes through packing material where heat transfer occurs. Air enters the tower from the bottom. Evaporative cooling takes place in a cooling tower which cools the water and is collected at the bottom of the tower (Chitale, Gamare, Chavan, Chavan, & Yekane, 2018). Water is supplied at about 90° F and returned to the cooling tower at a maximum of about 120°F (IPICEA, 2010). When water is cooled by evaporation in a cooling tower, it leads to loss of water in the refinery to atmosphere. These losses are referred to as cooling tower drift. Produced water can be introduced to account for cooling tower drift (IPICEA, 2010).Produced water must be treated to avoid adverse effect on Cooling Tower. Chemical compounds present in PW can cause corrosion, algae formation and fouling. Since impurities in PW have the potential to get accumulated in the system upon evaporation, the extent of treatment required for circulating systems is much greater (IPICEA, 2010).

1.2.1 Cooling tower water standards

Table 2 below presents the cooling tower limit of various water parameter (Louis E. Otts, 1963).

Table 2. Cooling Tower limit

Parameter	Cooling Tower Limit
COD (mg $O_2.L^{-1}$)	3.50
Turbidity (NTU)	1.00
TSS ($mg.L^{-1}$)	2.00
Chlorides ($mg.L^{-1}$)	22.00
Alkalinity ($mg.L^{-1}$)	26.00
Calcium ($mg.L^{-1}$)	30.00
Magnesium ($mg.L^{-1}$)	0.50
Sulfate ($mg.L^{-1}$)	22.00
Conductivity ($\mu S.cm^{-1}$)	165.0
Hardness ($mg.L^{-1}$)	30.00
Iron ($mg.L^{-1}$)	0.10
Manganese	0.5
pH	7.0-8.0
Silica	150

1.2.2 Equipment/ Method Overview

Electrodialysis reversal (EDR) and Reverse Osmosis (RO) were proposed to separate water from suspended solids and salts present in wastewater generated by petroleum industry. Prior to EDR and RO treatment step, PW is sent to sand filter and activated carbon filter to reduce Total Organic Carbon (TOC). EDR facilitates the removal of ions present in wastewater by applying an electric current. RO uses pressure as the driving force to retain contaminant present in wastewater through a semi-permeable membrane (Venzke, Giacobbo, Bernardes, & Rodrigues, 2017). The following section discusses the methods and equipment required to treat produced water to bring down the toxicity level of the water such that it meets the cooling tower limit.

2. Process Description

Produced water from oil field ($150\frac{m^3}{hr}$) at 34°C is collected and stored in tank (TK-101) after which it is sent to slow sand filter bed (T-101). Outlet stream from slow sand filter enters granular activated carbon filter (GAC) column. Outlet stream from GAC column is stored in tank (TK-102). $97.6\frac{m^3}{hr}$ of water from the tank is pumped to1st Electro dialysis Unit (ED-101). $94\frac{m^3}{hr}$ of water obtained from dilute stream of ED-101 is sent to 2nd ED Unit (ED-102). To enhance overall recovery of product stream, a portion of concentrate stream from ED-101 and ED-102 is recycled to ED-101. $88.36\frac{m^3}{hr}$ of treated water from ED-102 is then pumped to Reverse Osmosis unit (RO-101). Permeate stream from RO-101 meets cooling tower water standards after which it is sent to cooling tower unit.

Table 3 represents the removal efficiency of various equipment. General flow of processes for the proposed produced water treatment plant is schematically represented in figure 1.

Table 3. Compound Removal Efficiency of Various Equipment

Equipment	Compound Removed	Removal Efficiency
Slow Sand filter	TOG	40.0%
	TOC	25.0%
Activated Carbon filter	Chlorine	50.0%
	TOG	99.0%
	TOC	99.0%
Electro dialysis Reversal System	Chlorine	90.8%
	Sodium	89.4%
	Magnesium	96.7%
	Calcium	94.7%
Reverse Osmosis Unit	Chlorine	96.4%
	Sodium	95.3%
	Magnesium	96.0%
	Calcium	99.0%
	TOG	100.0%

Figure 1 below represents the process flow diagram designed to treat oilfield produced water.

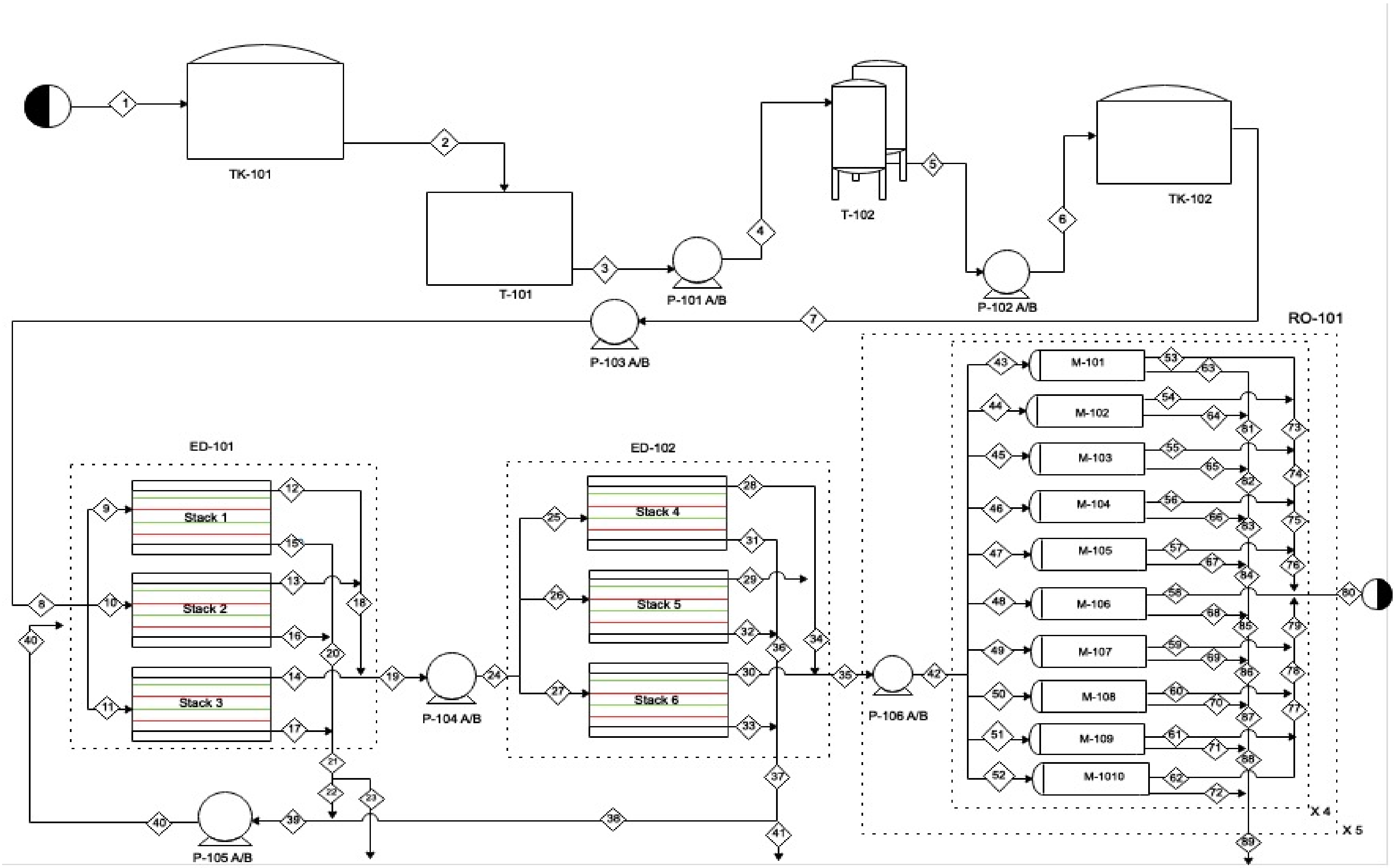

Figure 1. Process Flow Diagram

TK-101 and TK-102 are used to store PW at the inlet (Stream 1) and the outlet of T-102 (Stream 5) respectively. TK-101 has a storage capacity of 120 m^3 with a height of 8.40 m while TK-102 has a storage capacity of 115 m^3 with a height of 8.23 m. T-101 treats PW from storage tank to remove TOC and TOG (Stream 2). The outlet (Stream 3) is sent to Activated Carbon filter column (T-102). In T-101, the depth of the bed is 1.5 m with HLR of 0.4m/h, porosity of 0.4 and shape factor of 0.75. The total height of the filter adds up to 2.5m (Mavis & Wilsey, 1936). T-102 treats produced water from sand filter to remove TOC, TOG and chloride (Stream 4). The outlet (Stream 5) is sent to storage tank (TK-102). In T-102, the depth of the bed is 2 m with HLR of 5m/h, porosity of 0.65 and shape factor of 0.73 (Granular Activated Carbon). The total height of the filter adds up to 2.65 m. Granular activated carbon filter of 1875 kg is required which can be encased in a tank of 1.6 m diameter. The process requires 6 pumps of which 5 are centrifugal (P-101, P1-02, P-103, P-104, and P-106) and one is reciprocating pump (P-105). Centrifugal pumps are used when the flowrate to the equipment is big, (inlet and outlet to filters, EDR and RO) and reciprocating pump is used when flowrate is small (recycling part of waste stream, Stream 39). The diameter of suction and discharge pipe of the pump depends on flowrate. Table 4 represents the description of all the pumps used in the process (Turton, Bailie, Whiting, & Shaeiwitz, 2009).

Table 4. Description of pumps

Variables	P-101	P-102	P-103	P-104	P-105	P-106
Pump type	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Reciprocating	Centrifugal
Suction Diameter	10 in	10 in	12 in	12 in	2.5 in	16 in
Discharge Diameter	8 in	10 in	12 in	12 in	2.5 in	14 in
Pump Pressure	73.8 kPa	83.14 kPa	289.3 kPa	146.6 kPa	147.1 kPa	612.5 kPa
Total Head	6.6 m	7.4 m	25.8 m	13.1 m	13.1 m	54.7 m
NPSHA	13.9 m	18.7 m	6.9 m	19.6 m	19.6 m	19.6 m

The process requires 2 Electro Dialysis Reversal units which are represented as ED-101 and ED-102 in figure 1. Each unit comprises of 3 ED stacks which treats produced water to remove chloride, sodium, magnesium and calcium. ED-101 has an inlet capacity of 100 m^3/ hr of produced water. Feed flow rate of ED-101 comprises of outlet flow (Stream 8) of storage tank along with recycle concentrate (Stream 40). 10% of concentrate (Stream 21) is recycled (Stream 22). The dilute (Stream 19) recovered from process is sent to ED-102. Feed flow rate of ED-102 is 94 m^3/ hr. 94% of feed stream is recovered in the dilute stream after which it is channeled to Reverse Osmosis unit. 30% of concentrate stream (Stream 37) is recycled and introduced in ED-101 (Stream 40).

A typical industrial EDR stack accommodates 600-membrane pair. Up to 757 m^3/day of water can be desalted by 600-membrane pair (Gottberg, 1998). HDX 100 supplied by Hidrodex is used as cation-exchange membrane. It contains sulfonic acid groups as fixed ion-exchange sites. HDX 200 is used as anion-exchange membrane which has quaternary amines as fixed groups. Both the membrane has a characteristic thickness of 450 μm (Calatayud, et al., 2014). These membranes are separated and alternated by polypropylene spacers which have a thickness between 0.3 and 2 mm (Venzke, Giacobbo, Bernardes, & Rodrigues, 2017).Thickness of cell was found to be 3.2 mm and total height of the stack was determined to be 2.55 m.
The dimensions of the EDR unit were designed and calculated with the following formulae.

$$\text{Number of membrane pairs required} = \frac{600 \times \text{Dilute flow rate}}{757}$$

$$\text{Cell thickness} = (\text{Membrane height} + \text{Spacer height}) \times 2)$$

Reverse Osmosis operating at 8 bar presented 98.7% chloride removal from water (Venzke, et al., 2017). Pressure of permeate stream is around atmospheric pressure. The pressure drop between inlet of RO and the reject stream is less than 1 bar (Palacin). Feed for RO-101 (Stream 35) from ED-102 (Stream 36) dilute contains mainly chlorine and sodium ion. Permeate (Stream 80) composed of treated water meets cooling tower makeup water specification. Permeate is sent to cooling tower system. Concentrated stream post treatment is rejected from the RO-unit (Stream 89). Spiral wound modules are best suited for this operation as it is suitable for large-scale applications. It also has a high packing density thereby lowering membrane footprint and area occupied. The module is spiral wound with a packing density of 300 to 1000 m^2/m^3 which has an area of 95 m^2. The total number of modules required were found to be 200 using the below equation.

$$\text{Number of modules required} = \frac{\text{Area of membrane}}{\text{Area per module}}$$

Membrane selected for RO operation is polyamide membrane (Venzke, Giacobbo, Bernardes, & Rodrigues, 2017). Membrane area required to achieve 84% recovery is 1904.5 m^2 which was determined from the following equation.

Membrane area required, $A = \frac{Q_p}{A_w \times (\Delta P - \Delta \pi)}$, where Q_p is the permeate flow rate, A_w is the water permeability coefficient, ΔP is the operating and permeate pressure difference and $\Delta\pi$ is the osmotic pressure difference. Power rating of each equipment in the process is summarized below in table 5.

Table 5. Power requirement for each pump and EDR

Equipment	Power Required (kW)
P-101	1.756
P-102	1.979
P-103	11.21
ED-101	794.4
P-104	5.471
ED-102	69.07
P-105	0.135
P-106	21.47
P-107	21.47
P-108	21.47
P-109	21.47
P-110	21.47

3. Economic Feasibility

All chemical industries must perform profitability analysis before building the plant to estimate the profitability of the plant. A project life of 10 years was assumed to perform economic analysis (Turton, Bailie, Whiting, & Shaeiwitz, 2009).

3.1 Fixed Capital Investment (FCI)

The following steps were followed to calculate the Fixed Capital Investment (Grass Root Cost).

3.1.1 Equipment Cost

First equipment cost, C_p^0, was calculated using the following equation:

$$\log C_p = K_1 + K_2 \log A + K_3 (\log(A))^2$$

where C_p is cost per size parameter ($/A), K_1, K_2, K_3 are constants for each equipment and A is the capacity or size parameter.

3.1.2 Bare Module Cost

The bare module cost (capital cost), is then calculated with the following formulae:

$$C_{BM} = C_P^0 (F_{BM})$$

$$C_{BM} = C_P^0 (B_1 + B_2 F_P F_M)$$

where C_{BM} is the bare module cost, C_p^o is the equipment cost., F_{BM} is the bare module factor, F_p is the pressure factor, F_M is the material factor and B_1 and B_2 are the bare module constants.

3.1.3 Pressure Factor

The pressure factor is calculated by the below equation:

$$\log_{10} F_P = C_1 + C_2 \log_{10} P + C_3 (\log_{10} P)^2$$

where P is the pressure in barg and C_1, C_2, C_3 are the constants pressure factor (Turton, Bailie, Whiting, & Shaeiwitz, 2009).

3.1.4 Cost in 2019

Lastly, to find the cost at a specific year, the following equation is used $C_2 = C_1 \left(\frac{I_2}{I_1}\right)$ where I represent the CEPCI index and C represents the cost.

3.1.5 Capital Cost of Pumps, Storage Tanks, and Filters

Table 7 represent the summary of the estimation used to find the capital cost of the mentioned equipment.

Table 7. Capital Cost of Pumps, Storage Tanks, and Filters

Equipment Name	Equipment Description	A	K_1	K_2	K_3	C_P^0	F_{BM}	B_1	B_2	F_M	F_P	$C_{BM}(2001)$	$C_{TM}(2001)$
P-101	Centrifugal	1.229	3.3892	0.0536	0.1538	2482.46	-	1.89	1.35	1.6	1	10,062.09	11,873.27
P-102	Centrifugal	1.385	3.3892	0.0536	0.1538	2511.07	-	1.89	1.35	1.6	1	10,169.84	12,000.41
P-103	Centrifugal	7.850	3.3892	0.0536	0.1538	3633.51	-	1.89	1.35	1.6	1	23,741.62	17,364.56
P-104	Centrifugal	3.82	3.3892	0.0536	0.1538	2968.28	-	1.89	1.35	1.4	1	11,220.12	13,239.74
P-105	Reciprocal	0.09	3.3489	0.3161	0.122	4703.88	-	1.89	1.35	1.6	1	19,050.72	22,479.85
P-106	Centrifugal	15	3.3892	0.0536	0.1538	4623.52	-	1.89	1.35	1.6	1	18,725.28	$22,095.83
P-107	Centrifugal	15	3.3892	0.0536	0.1538	4623.52	-	1.89	1.35	1.6	1	18,725.28	22,095.83
P-108	Centrifugal	15	3.3892	0.0536	0.1538	4623.52	-	1.89	1.35	1.6	1	18,725.28	22,095.83
P-109	Centrifugal	15	3.3892	0.0536	0.1538	4623.52	-	1.89	1.35	1.6	1	18,725.28	22,095.83
P-110	Centrifugal	15	3.3892	0.0536	0.1538	4623.52	-	1.89	1.35	1.6	1	18,725.28	22,095.83
TK-101	Storage Tank	375	4.8509	-0.3973	0.1445	61,043.85	1	-	-	-	1	61,043.85	72,031.74
TK-102	Storage Tank	60	4.8509	-0.3973	0.1445	39,932.24	1	-	-	-	1	39,932.24	47,120.05
T-101	Sand Filter	200	3.2107	-0.2403	0.0027	469.95	1.65	-	-	-	-	775.42	915.00
T-102	Activated Carbon Filter	18.87	3.2107	-0.2403	0.0027	810.05	1.65	-	-	-	-	1,336.59	1,577.18
SUM (2001)												$ 160956.9	$ 189929.15
SUM (2019)												**$ 259679.84**	**$ 306425.21**

3.1.6 Capital Cost of Electrodialysis Reversal Unit

Cost of EDR was estimated using information through literature review and estimation where membrane area was found to be 0.4692 m^2, spacer area of 0.34 m^2, 6 stacks, and 12 electrodes. In addition, total number of membrane and spacer was estimated to be 7200 and 7188 respectively (Jaberi & Ghassemi, 2015), (Martí-Calatayud, Buzzi, García-Gabaldón, Bernardes, & Pérez-Herranz, 2014). Table 8 and 9 shows the cost estimation for EDR unit.

Table 8. Capital Cost estimation of Electrodialysis Reversal

Component	Unit Cost	Total no.
Membrane	$\$25/m^2$	7200
Spacer	$\$4/m^2$	7188
Stack frame	\$5 per pc	6
Electrode	\$77 per pc	12

Table 9. Capital Cost estimation of Electrodialysis Reversal

Cost of membrane (2002)	Cost of spacer (2002)	Cost of stack frame (2002)	Cost of electrode (2002)	C_{BM} (2002)	C_{TM} (2002)
84,456	9,775.68	30	570.70	94,832.38	111,902.21
Sum (2019)			**924**	**153,539.28**	**181,176.35**

3.1.7 Capital cost of Reverse Osmosis

Cost of reverse osmosis was also estimated through literature review. Cost of one membrane module was estimated to be \$605, the RO unit has 200 modules resulting the bare module cost for RO to be \$121,605. Total cost for RO was calculated to be \$ 171,694 in 2019.

Using the above information, Grass Root Cost was estimated using the formula

$$C_{GR} = (0.5 \times C_{BM}) + C_{TM}$$

where $C_{BM}$is the bare module cost which was found to be \$672,417 and C_{TM} is the total module cost which was found to be \$852,711.

The grass root cost (2019) which is also known as the fixed capital investment amount was estimated to be \$1,188,920.

3.2 Cost of Manufacturing (COM)

The cost of manufacturing (COM) for a chemical plant consist of direct costs, fixed cost, and general expenses. Cost of raw materials, utilities, and operating labor are considered as direct cost while cost of depreciation (equipment) and local taxes are considered as fixed cost.

Cost of manufacturing with and without depreciation can be calculated using the following equation:

With depreciation

$$\mathrm{COM} = 0.280\mathrm{FCI} + 2.73C_{OL} + 1.23 \times (C_{UT} + C_{RM} + C_{WT})$$

Without depreciation

$$\mathrm{COM}_d = 0.18\mathrm{FCI} + 2.73C_{OL} + 1.23 \times (C_{UT} + C_{RM} + C_{WT})$$

3.2.1 Cost of Raw Materials

The cost of raw material which is produced water for this process has zero cost as the water is considered as a waste or by product with zero use potential.

3.2.2 Cost of Labor

First, the number of labors required for the number of equipment in the process was estimated in table 10.

Table 10. Estimation of Nnp

Equipment	Number	Nnp
Tank	2	-
Pump	7	-
Sand Filter	1	1
Activated carbon Filter	1	1
Electrodialysis Reversal	2	2
Reverse Osmosis	2	2
Sum		6

The following equation is used to find N_{np}, $N_{np} = \sum \text{Equipment}$
N_{np} is the number of non-particulate processing steps and includes compression, heating, and cooling, mixing, and reaction.
Next, the operating labor required for chemical processing plants was estimated from the following equation:
$N_{OL} = \left(6.29 + 31.7P^2 + 0.23N_{np}\right)^{0.5}$ where P is the number of processing steps involving the handling of particulate solids (=0). $N_{OL} = 6.29 + (0.23 \times 6) = 2.769$
Then, Shifts per operator per year = $49\frac{\text{weeks}}{\text{year}} \times 5\frac{\text{shifts}}{\text{week}} = 245 \text{ shifts per operator per yr.}$

$$\text{Stream factor} = \left(\frac{\text{Number of operational days per year}}{365}\right)$$

Stream Factor value has a range from 0.9 to 0.96. Average of the stream factor was taken which is equal to 0.93
Number of operational days per year was calculated to be 340 days per year.
$340 \text{ days/year} \times 3 \text{ shifts/day} = 1020 \text{ operating shifts per year}$

$$\text{Operating}\frac{\text{shifts}}{\text{year}} = \text{Number of operational days per year} \times \frac{\text{operational hours}}{\text{Time per shift}}$$

$$= 320 \times \frac{15}{8} = 637.5 \text{ operating}\frac{\text{shifts}}{\text{year}}$$

The number of operators required to provide 1960 shifts are:

$$637.5(\text{shifts/yr}) \;/\; (245\ (\text{shifts/operator/yr}) = 2.602 \text{ operators}$$

The operating labors required are $2.769 \times 2.602 = 7.2063$ operators which is equal to 8 laborers
An average cost for labor in $/year (2006) is $55,000 for 2000 working hours (Turton, Bailie, Whiting, & Shaeiwitz, 2009).The total labor cost is found as shown in the Table 11.

Table 11. Estimate Cost for Labor

Total plant operation time (hr)	15
Time per shift (hr)	8
Shifts /operator/year	245
operating shifts/year	637.5
Number of operators	2.6
Operating labor	7.2
Cost of labor / year (2006) for 2000 hr	$ 55,000
Cost of labor / year (2006) for 1 hr	$ 27.50
Number of hours	1960 hr
Cost of labor / year (2006) for 1960 hr	$ 53,900
Total cost for the labor (2006)	$431,200
Cost of labor / year (2019)	**$ 573,638**

3.2.3 Cost of Utilities

The only utility required for this plant is electricity for pump and electrodialysis reversal unit.

The unit cost of the utility was found through literature review. The following table 12 summarizes the calculations for the total cost of utilities.

Table 12. Utility Cost Estimation

Equipment	**A(kW)**	**Efficiency**	**Electric Power (kW)**	**Energy (kWh/year)**	**Cost ($/kWh)**	**($/year) 2001**	**($/year) 2019**
P-101	1.229	0.7	1.75	8954.142857	0.06	537.25	872.71
P-102	1.385	0.7	1.978	10090.71429	0.06	605.44	983.48
P-103	7.85	0.7	11.21	57192.85714	0.06	3,431.57	5,574.24
P-104	3.82	0.7	5.45	27831.42857	0.06	1,669.89	2,712.56
P-105	0.09	0.7	0.128	655.7142857	0.06	39.34	63.91
p-106	15	0.7	21.42	109285.7143	0.06	6,557.14	10,651.41
P-107	15	0.7	21.42	109285.7143	0.06	6,557.14	10,651.41
P-108	15	0.7	21.42	109285.7143	0.06	6,557.14	10,651.41
P-109	15	0.7	21.42	109285.7143	0.06	6,557.14	10,651.41
P-110	15	0.7	21.42	109285.7143	0.06	6,557.14	10,651.41
ED-101	414.68	0.7	592.40	3021241.289	0.06	181,274.48	294,461.84
ED-102	36.06	0.7	51.50	262696.9301	0.06	15,761.82	25,603.46
					Sum	236,105	383,529

After calculation of the cost of raw material, utilities and operating labor, manufacturing cost was calculated
COM (taking depreciation into account) =$2,370,213.82
$\mathrm{COM_d} = \$2{,}251{,}490$

4. Conclusion

In this project it was shown that by using water treatment plant that comprises of EDR and RO units, a huge amount of produced water can be treated to meet cooling tower requirements. By using the proposed treatment plant both environmental and waste minimization problems were addressed. Reusing produced water in petroleum refinery was identified as the best means to manage produced water. An economical study was conducted on the process plant focusing on capital cost and manufacturing cost. Overall recovery of the treatment plant was found to be 75.9% of feed produced water that could be sent to cooling tower unit. The treatment capacity of the plant is $1500\,\frac{\mathrm{m^3}}{\mathrm{hr}}$ of produced water in 15 to 16 hours. The treatment plant required 2 storage tanks, 1 sand filter, 1 activated carbon filter, 9 centrifugal pumps, 1 reciprocating pump, 6 EDR stacks and 200 RO modules. Recovery ratio for EDR stacks were 94% with recycle and 84% for RO unit. The Fixed Capital Investment required for the plant was estimated to be $ 1,188,920.

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Biographies

Chandra Mouli R. Madhuranthakam is an assistant professor in the department of chemical engineering at the Abu Dhabi University, Abu Dhabi, United Arab Emirates. He earned B.Tech in chemical engineering from Sri Venkateswara University, India Master's in chemical engineering at the Indian Institute of Science, Bangalore, India and PhD in chemical engineering University of Waterloo, Canada. He is a member of the American Institute of Chemical Engineers and the Institute for Operations Research and Management Sciences (INFORMS).

Archana Thomas was an undergraduate student in chemical engineering department graduated recently from Abu Dhabi University.

Zainab Akhter was an undergraduate student in chemical engineering department graduated recently from Abu Dhabi University.

Ali Elkamel is a professor in the department of chemical engineering at University of Waterloo, Waterloo, Canada. He earned his B.S. and M.S. in chemical engineering at Colorado School of Mines and PhD in chemical engineering at Purdue University. Ali Elkamel is also a visiting Professor in the Department of Chemical Engineering at Khalifa University, Abu Dhabi, UAE. He is a member of the Canadian Society for Chemical Engineering, the American Institute of Chemical Engineers, the Canadian Operational Research Society, and the Institute for Operations Research and Management Sciences (INFORMS).