8-2024

# Techno-Economic and Environmental Assessments of Produced Water Treatment Technologies for Beneficial Reuse

Elora Afrin

Research Project Report

for

Non-Thesis Track

# Techno-Economic and Environmental Assessments of Produced Water Treatment Technologies for Beneficial Reuse

by

Elora Afrin

Department of Natural Sciences

Texas A&M University-San Antonio

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN WATER RESOURCES SCIENCE AND TECHNOLOGY

August, 2024

# Techno-Economic and Environmental Assessments of Produced Water Treatment Technologies for Beneficial Reuse

## Abstract

Produced water (PW) is a bulk portion of byproduct generated during oil and gas extraction operations and can be potentially reused for various purposes. However, the treatment costs and associated environmental issues call for a multitude of factors for proper management. This research aims to evaluate the viability of technologies for treating PW in terms of their technical performance, cost-effectiveness, and environmental considerations. Technologies evaluated include well-established processes such as electrodialysis (ED), electrodialysis reversal (EDR), ion exchange, chemical oxidation, electrocoagulation (EC), chemical coagulation (CC), nanofiltration (NF) etc. Associated case studies have been studied. However, except EC and CC, other technologies fail to purify highly saline PW for beneficial reuses, such as Permian Basin PW. Among those five technologies, EC and CC are most cost-effective processes as their costs are \$0.44/m$^3$ and \$0.26/m$^3$, respectively. They are the most environmentally friendly as they consume less energy and since the treated water is eligible for onsite reuse, there are no air emission and traffic issues associated with transportation. Whereas, the most expensive one is the NF process and its cost ranges between \$0.8337-\$4.0407/gallon and the NF process that has been indicated in this paper is not eligible to treat Permian Basin PW up to any of the reuse criteria. Coagulation, flocculation processes and specific electrodialysis setup can be applied as pretreatment. However, there is no sufficient evidence to support their success. Two series of operations have been proposed. One of them is a combined electrocoagulation-microfiltration-membrane distillation process and another one is a series operation consisting of hydrocyclone, coagulation/flocculation, MVC, membrane bioreactor, and UV/$H_2O_2$ process. The required costs of these technologies have been discussed and concluded that the PW that contains total dissolved solids (TDS) value exceeding 100,000 mg/L, cannot be treated up to the standard for beneficial purposes like irrigation, livestock feeding at low cost. The estimated cost for the successful series operation is approximately \$1.01/bbl. Since such series of operation can provide reusable water for multiple purposes, these can be considered as environment friendly technologies.

# Contents

## List of Figures

## List of Tables

# 1. Introduction

## 1.1. Produced Water

Natural or formation water is always present alongside petroleum in reservoirs. It has a slight acidity and remains beneath the hydrocarbons within the porous reservoir media. When oil and gas are extracted, the reservoir pressure decreases. To counteract this, additional water needs to be injected into the reservoir's water layer to balance hydraulic pressure and improve oil recovery (Igunnu et al., 2012). Along with the water injected into the reservoir, water can also seep in from outside the reservoir area. As oil and gas production progresses, eventually the formation water will reach the production well, resulting in the extraction of water along with hydrocarbons. This water, referred to as produced water or oilfield brine, constituents the largest volume of byproduct produced during oil and gas extraction operations. (Chan et al., 2002; Reynolds et al., 2003).

## 1.2. Scope of Problems

Oil and gas production operations generate 20 to 30 billion barrels of produced water each year. This is 70 times the volume of all liquid hazardous wastes generated in the U.S. (Otton & Mercier [n.d.] Produced water brine and stream salinity [Otten.pdf (usgs.gov)]). A complex factor for water management in oil and gas facilities arises from the emergence of unconventional sources, i.e., shale gas, oil, sands, and tar sands. Such sources can demand even greater water usage as compared to unconventional methods, especially during drilling and hydraulic fracturing processes. Produced water is highly contaminated, and its constituents are highly variable because it depends on the technologies utilized during extraction, its geological position, minerals available in that geological formation, types of hydrocarbons being extracted. Produced water is highly saline, ranging from nearly fresh (≤ 1%) to approximately 50% which is almost 15 times saltier than seawater (Allison et al., 2018) with a high amount of total dissolved solids (TDS). Volatile, non-volatile, and semi-volatile organic compounds like BTEX (benzene, toluene, ethylbenzene and xylene) and PAHs (polycyclic aromatic hydrocarbons) are also major constituents. Moreover, naturally occurring radioactive materials (NORMs) and heavy metals are not uncommon to produced water (Rodriguez et al., 2020). Due to vast amounts of contaminants particularly excessive TDS, treating such PW to meet potable, irrigation and livestock watering is not a cost-effective solution. Consequently, well injection is the most common way to manage produced water. According to the Underground Injection Control program, there are six classes of injection wells. Partially treated PW is injected into deep underground into a geologically isolated formation. Meanwhile, PW could potentially escape from this formation and contaminate surface or groundwater sources (Alessi et al., 2015). Usually, produced water is injected into the Class II well. Deep well injection may be a potential reason for seismic hazards including unexpected tectonic activities. In addition to the well injection disposal cost, these costs include transportation, capital and infrastructure maintenance, which may be as much as $4.00/bbl (Kassab et al., 2021).

### 1.3. Objectives

The constituents of PW are highly variable as well as the treatment, efficiency, purpose and management also depend on each particular case. However, a general overview would help to understand the technological options and decide which technology should be pursued for their specific purposes. The objectives of this research report are to present key technologies that can treat extremely high saline water (TDS> 100,000 mg/L), which can be reused in different sectors along

with their costs and impact on the environment. Firstly, some simple technologies have been discussed which were able to treat PW for specific reuse purposes. Afterwards, their removal efficiencies were applied mathematically to Permian Basin PW and observed whether the effluent water may meet any reuse criteria. The costs and environmental issues associated with each technology have also been assessed. Finally, two hybrid multi-stage processes have been discussed, which are highly efficient in treating extremely polluted water and can provide quality water by reducing the contaminants to be in accordance with U.S.EPA standards of different beneficial reuse.

## 2. Literature Review

Figure 1 shows the seven most prominent oil and gas development locations. The Permian Basin, including Midland and Delaware Basin in West Texas and Southeast New Mexico, is one of the largest and most prolific oil and gas producing regions in the United States. It has seen significant development due to advancements in hydraulic fracturing and horizontal drilling. Other O&G development basins include Eagle Ford, Appalachian (including Utica and Marcellus Basins), Basin in-Pennsylvania, Ohio, and West Virginia, Bakken Play in North Texas, Rocky Mountain Basin in-Colorado, Wyoming, Utah, Northwest New Mexico, and Haynesville Basin in Arkansas, Louisiana, and Texas. (The GWPC Produced Water Report: Regulations & Practices, May 2023, Ground Water Protection Council [GWPC Releases 2023 Produced Water Report | Ground Water Protection Council]).

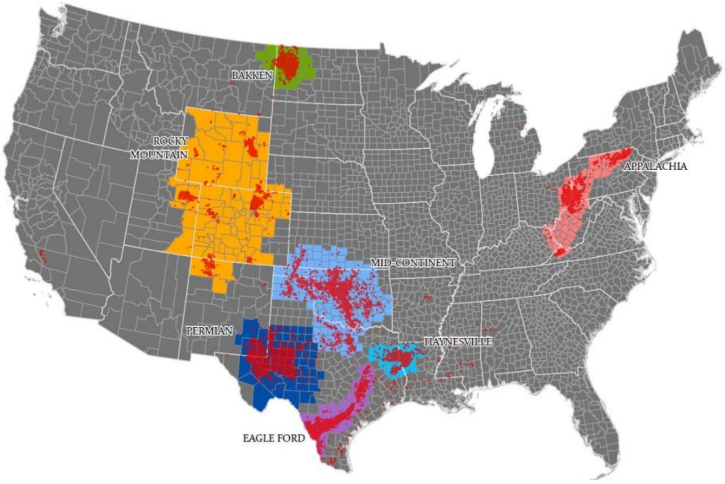


Figure 1: Seven most prominent oil and gas development regions in the continental US. (Source: Produced water report Regulations and Practices Updates GWPC, 2023)

### 2.1 Techno-Economic Data

### 2.1.1 ED/EDR

#### Coagulation-ED

An operation was conducted with an integrated approach combining coagulation and electrodialysis to treat PW. In the ED system, ion removal efficiency was analyzed to assess the desalination effect. The removal rate of ions reached up to 91% with the exception of $SO_4^{2-}$, which had a removal rate of 84.3% (Hao et al., 2014). The treated water met the standards for wastewater reclamation. The PW was sourced from the Shengli Oilfield in Dongying City, Shandong, China. Polyaluminum chloride (PAC) and polyacrylamide (PAM), both of analytical grade were used directly as a coagulant and a coagulation aid respectively in the pretreatment system without further purification.

The cost for this specific operation is not available. However, the price of PAC is $272.00-355.00/ton and the price of PAM is $1750/ton.

#### RO-EDR

A hybrid technology RO and EDR was utilized using PW from a petrochemical industry in southern Brazil. This study aimed to enhance water recovery utilizing a hybrid process of RO and EDR. The EDR was employed to recover water from the reject generated by RO technology. The raw PW initially underwent conventional treatment involving biological processes and stabilization ponds. The results showed that the EDR technology effectively treated the RO reject, achieving a removal efficiency of over 90% for chlorides and alkalinity. The recovered water met the standards for reuse in cooling towers. Additionally, the overall water recovery was successful, with a recovery rate of 87.3%, making the EDR-RO process highly promising. (Venzke et al., 2018).

The cost of this specific operation is not available. However, a general estimated cost for ED/EDR is 8000 bbl/day treatment train of coal bed methane (CBM) produced water is estimated to cost 15 cents per barrel (Igunnu et al., 2014). While, the total costs depend on feed water TDS and site location. For RO, the capital cost of BWRO varies from \$35 to \$170/bpd and operating costs are ~0.03/bbl. The capital cost of SWRO varies from \$125/bpd (barrel per day) to \$295/bpd and the operating cost is ~0.08/bbl.

### 2.1.2. Chemical Oxidation

Batch ozone-photocatalytic oxidation ($O_3/UV/TiO_2$) and a post-biological treatment using microalgae can provide such quality of PW which can be eligible for surface discharge (Corrêa et al., 2010). The effectiveness of this hybrid advanced process followed by biological treatment was evaluated through physicochemical time-course analysis and ecotoxicological tests. Results showed that after 5 minutes of treatment with $O_3/UV/TiO_2$, phenol concentration decreased by 99.9%, sulfide by 53.0%, COD by 37.7%, O&G by 5.2% and ammonia by 1.9%. After 60 minutes of oxidation treatment, reductions were observed in phenols (99.9%), O&G (98.2%), sulfide (97.2%), COD (89.2%) and ammonia (15%). Acute toxicity tests with the bacterium *Vibrio fischeri* (Lumistox) and the fish *Poecilia vivipara* showed high toxicity in raw effluents ($EC_{50}$=1.55% for both species). However, after 60 minutes of treatment, effluents exhibited lower acute toxicity toward bacteria ($EC_{50}$=30.9%), though toxicity toward fish remained high ($EC_{50}$=1.9%). Subsequent PW biotreatment with macroalgae *Ulva spp*. Significantly reduced toxicity ($EC_{50}$=89.2% for bacteria and $EC_{50}$=85.7% for fish), attributed to the biosorption and transformation of metals and ammonia compounds during biological treatment. Thus, physicochemical results indicated that combining 10 minutes of $O_3/UV/TiO_2$ treatment followed by macroalgae depuration is a promising, cost-effective option for PW stream.

The cost of this particular case is not available. However, in general the capital cost is about \$0.01/gpd. Operation and maintenance costs are about \$0.01/bbl for chemical oxidation (Igunnu et al., 2014). According to Esplugas et al., (1997), if the contaminant is biodegradable, then capital and operational expenditures are less for biological treatment than for advanced oxidation processes (AOPs).

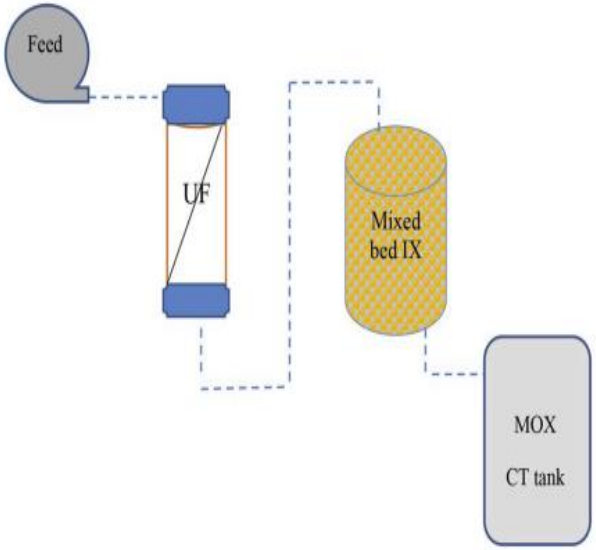
### 2.1.3. EC and CC

A study was conducted to create cost-effective technologies and optimize systems and operations to treat highly saline produced water (120-140 g/L total dissolved solids) for use in hydraulic fracturing. Produced water samples were obtained from a saltwater disposal facility in the Permian Basin, New Mexico. The research compared chemical coagulation (CC) using ferric chloride and aluminum sulfate with electrocoagulation (EC) using aluminum electrodes to remove suspended contaminants. It also examined how coagulant dosage, current density, and hydraulic retention time during EC affect turbidity removal. During chemical coagulation, alum achieved higher turbidity removal compared to ferric chloride at the same molar concentration, leading to lower chemical demand and cost. To achieve 60% turbidity removal from the produced water, 36 mg/L Al (III) (444 mg/L $Al_2(SO_4)_3.18H_2O$) and 134 mg/L of Fe (III) (650 mg/L $FeCl_3.6H_2O$) were required as coagulants (Rodriguez.et al., 2019).

The total operating costs, which include both electrical power and chemical expenses, were estimated to be approximately \$0.26/m$^3$ for aluminum and \$0.37/m$^3$ for iron coagulation. After coagulation, the remaining fine particles and contaminants were treated using continuous-flow packed columns packed with various filter media including agriculture waste products (pecan shell, walnut shell, and biochar), along with new and spent granular activated carbon (GAC). The system's performance was evaluated by monitoring turbidity, total organic carbon (TOC), metals, and electrical conductivity to determine the adsorption capacities of the different media. Biochar and GAC were the most effective in reducing turbidity and TOC in the PW. These treatment methods effectively removed suspended particles and iron, resulting in clean brine that could be reused onsite, such as for hydraulic fracturing (Rodriguez.et al., 2019).

### 2.1.4. Ion Exchange in Hybrid Technology

In the real world, ion exchange, and NF technologies are mostly used in combination with other technologies to achieve particular standards for particular purposes. For example, ultrafiltration, ion exchange and MOX disinfection. MOX disinfectant can be produced in-situ by the NaCl electrolysis process. A study was conducted to document the economic assessments of this integrated process. At an ideal Trans Membrane pressure of 1 bar, the removal efficiencies achieved were as follows: COD (57%), TDS (80%), Turbidity (94%), $SiO_2$ (67%), Oil (88%), and HPC (99%) (Hashemi et al., 2020). The integrated processes effectively reclaimed oily effluents to supply makeup water for cooling towers. An overview of the cost parameters and economic values used in the economic assessment of full-scale integrated treatment method to provide 50 $m^3$/h (1200 $m^3$/day) of makeup water. Considering the annual fixed capital expenditure (CAPEX) and variable operating expenditure (OPEX), the reclamation cost for 1 $m^3$ of the refinery's industrial effluent for use as makeup water was calculated to be $0.24. The total initial investment required for installing this effluent treatment system was estimated at $255,750 (Hashemi et al., 2022). The most expensive aspect of this scenario is the use of chemicals for regenerating and washing membranes. To produce 1 kg of MOX, 3.5kg of salt and 4.5kW of electricity are needed. Annually, the cost of purchasing 12 tons of salt (at $0.05/kg) for producing 3460L of MOX is estimated at $600. In comparison, the oil refinery currently uses calcium hypochlorite (perchlorate) at a rate of 15 kg/day for disinfecting makeup water, which is approximately 5.5 tons per year. The annual cost for this perchlorate, at $1.2/k, is about $6600. This is significantly higher than the $600 annual cost for the salt needed to produce MOX. The diagram below shows the expense and removal efficiencies in each stage (Hashemi et al., 2022).



Membrane type=Polysulfone
Efficiency:
TDS=27%
Turbidity=83%
COD=47%
SiO2=19%
O&G=52%
capital costs ~$1 - $2/gpd
O&M costs ~$1 to $2/kgal

Resin type=Mixed bed IX (SBA with functional groups –$NH_3OH$) (SAC with functional groups: $SO_3H$ in down layer)
Efficiency:
TDS=80%
COD=The IX process had no effect on COD reduction
Turbidity=67%
SiO2=60%
O&G=63%
SAC resin:
Operating Capacity: 18 kgr/Cu.Ft. at 15 lbs/Cu.Ft.
Cost per 1000 kgr: $10.80

Resin type=Mixed bed IX (SBA with functional groups –$NH_3OH$) (SAC with functional groups: $SO_3H$ in down layer)
Efficiency:
TDS=80%
COD=The IX process had no effect on COD reduction
Turbidity=67%
$SiO_2$=60%
O&G=63%
SAC resin:
Operating Capacity: 18 kgr/Cu.Ft. at 15 lbs/Cu.Ft.
Cost per 1000 kgr: $10.80

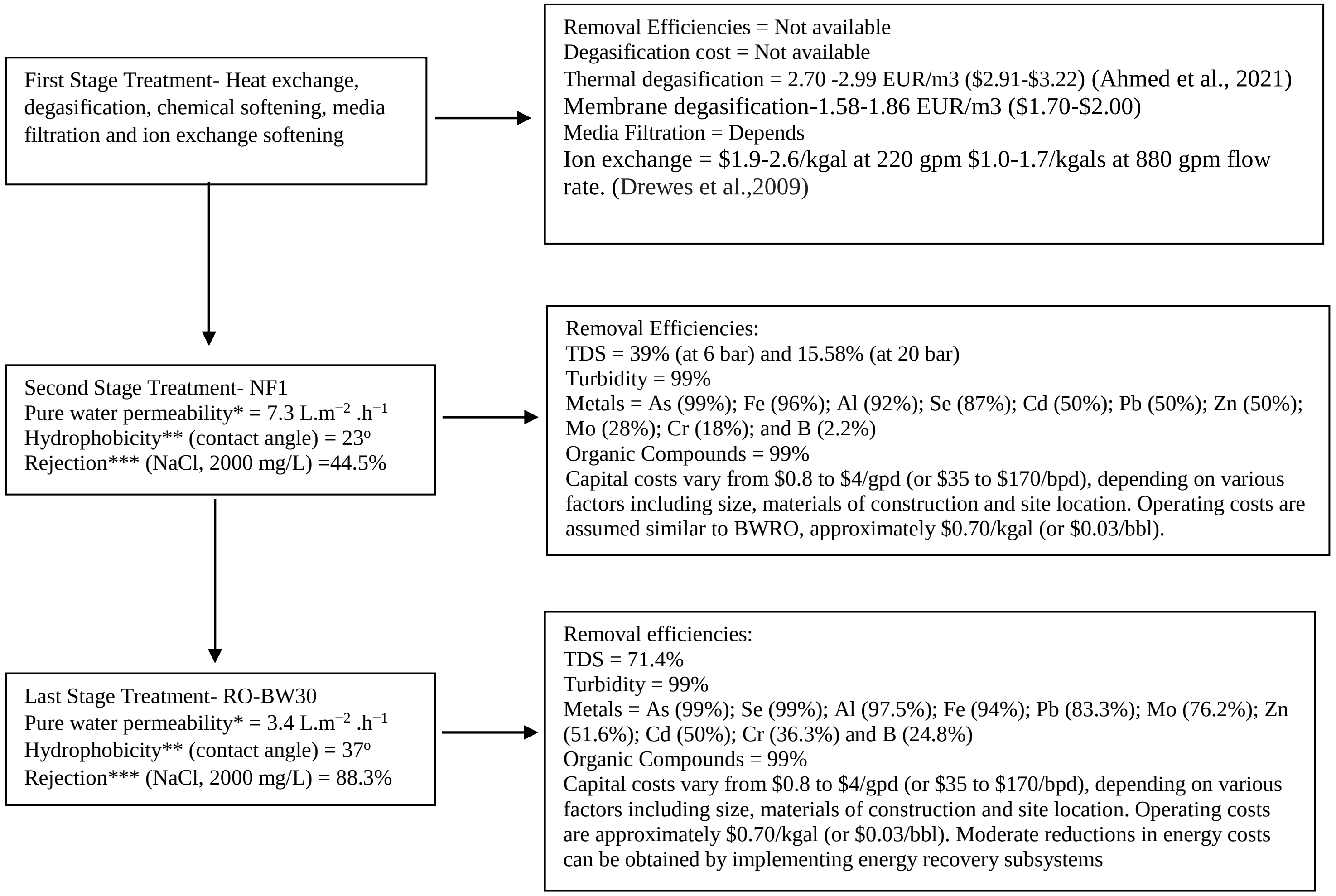
Figure 2: Ion exchange process with pre-treatment and MOX disinfection step.

### 2.1.5. Nanofiltration

Recently, there have been three projects focused on treating PW with membrane technology. The aim is to convert produced water into a usable resource, particularly for drinking water. The first project was initiated by Chennai Petroleum Company Limited (CPCL). They installed membrane units (UF as a pre-treatment and RO as a post-treatment step) at their refinery in Chennai. The refinery provided 60% of its treated PW into the water sources for the nearby Chennai community (Alzahrani et al., 2013). The second innovator was the San Ardo water reclamation project in California. It stands out as the most extensive use of RO membrane technology (as a post-treatment step) for treating the upstream processes of the petroleum industry. The facility generates over 50,000 barrels per day of treated PW. This water is then reused to replenish the groundwater basin and provide fresh water. The treatments involve heat exchange, degasification, chemical softening, media filtration and ion exchange softening for the RO feed. The third project was in Wellington, Colorado, USA. They used membrane technology, such as Ceramic MF and RO. The initial treatment phase involved dissolved air floatation, pre-filtration, ceramic MF membranes, and activated carbon adsorption. The purified water from the RO membrane provided over 93,600 gallons of potable water for the residents of Wellington. The key finding from these three case studies demonstrates that membrane technology shows the greatest promise in the final phases of PW water treatment either as a pre or post-treatment approach.

A study was conducted to compare the performance of NF and RO according to their removal efficiencies. Based on the evaluation of 103 parameters in produced water treated with NF, it was found that post-filtration samples from NF membranes effectively decrease contaminants, except for ammonia and molybdenum. This indicates that NF membranes could serve as a pretreatment before RO membranes to recycle treated produced water for indirect drinking purposes. Moreover, NF membranes showed remarkable removal efficiencies, lowering turbidity levels to undetectable levels. This effectiveness could help reduce the risk of organic fouling in RO membranes.

The total cost is \$0.8337-\$4.0407/gallon including capital and operational costs.



First Stage Treatment- Heat exchange, degasification, chemical softening, media filtration and ion exchange softening

Removal Efficiencies = Not available
Degasification cost = Not available
Thermal degasification = 2.70 -2.99 EUR/m3 (\$2.91-\$3.22) (Ahmed et al., 2021)
Membrane degasification-1.58-1.86 EUR/m3 (\$1.70-\$2.00)
Media Filtration = Depends
Ion exchange = \$1.9-2.6/kgal at 220 gpm \$1.0-1.7/kgals at 880 gpm flow rate. (Drewes et al.,2009)

Second Stage Treatment- NF1
Pure water permeability* = 7.3 L.m$^{-2}$ .h$^{-1}$
Hydrophobicity** (contact angle) = 23°
Rejection*** (NaCl, 2000 mg/L) =44.5%

Removal Efficiencies:
TDS = 39% (at 6 bar) and 15.58% (at 20 bar)
Turbidity = 99%
Metals = As (99%); Fe (96%); Al (92%); Se (87%); Cd (50%); Pb (50%); Zn (50%); Mo (28%); Cr (18%); and B (2.2%)
Organic Compounds = 99%
Capital costs vary from \$0.8 to \$4/gpd (or \$35 to \$170/bpd), depending on various factors including size, materials of construction and site location. Operating costs are assumed similar to BWRO, approximately \$0.70/kgal (or \$0.03/bbl).

Last Stage Treatment- RO-BW30
Pure water permeability* = 3.4 L.m$^{-2}$ .h$^{-1}$
Hydrophobicity** (contact angle) = 37°
Rejection*** (NaCl, 2000 mg/L) = 88.3%

Removal efficiencies:
TDS = 71.4%
Turbidity = 99%
Metals = As (99%); Se (99%); Al (97.5%); Fe (94%); Pb (83.3%); Mo (76.2%); Zn (51.6%); Cd (50%); Cr (36.3%) and B (24.8%)
Organic Compounds = 99%
Capital costs vary from \$0.8 to \$4/gpd (or \$35 to \$170/bpd), depending on various factors including size, materials of construction and site location. Operating costs are approximately \$0.70/kgal (or \$0.03/bbl). Moderate reductions in energy costs can be obtained by implementing energy recovery subsystems

Figure 3: NF process with pre-treatment and post-treatment using RO-BW30, including stage-wise removal efficiencies and associated costs

The five case studies discussed successfully treated PW for a specific reuse purpose. Each case study with a corresponding reuse purpose is presented in Table 2. Except for EC and CC, all of the PW utilized here had lower salinity and the TDS value was not more than 5000 mg/L.

Table 1: Techno-economic overview of five key treatment technologies

| **Technologies** | **Removal Efficiency in associated case studies** | **Energy Consumption** | **Chemical Consumption** | **Pre-Treatment/ Post-Treatment** | **Cost** |
|---|---|---|---|---|---|
| ED/EDR | Ions removal up to 84-91% for Coagulation-ED hybrid process (Hao et al., 2014) and 90% for EDR-RO hybrid process (Venzke et al., 2018) | Energy type: electricity. 0.14-0.20 kWh/lb, NaCl equivalent removed | Scale inhibitor required to prevent scaling. Acid, caustic disinfectant, EDTA and other antiscaling chemicals are required for cleaning and process control | Filtration of fouling and scaling substances in addition to solid particles is a necessary pre-treatment. Remineralization of product water is also necessary for SAR adjustment and disinfection | Total costs depend on feed water TDS and site location. 8000 bbl/day treatment train of CBM produced water is estimated to cost 15 cents (\$0.15) per barrel |
| Chemical Oxidation | Batch ozone-photocatalytic oxidation ($O_3$/UV/$TiO_2$) phenols 99.9%, O&G 98.2%, sulfide 97.2%, COD 89.2%, and ammonia 15% (Correa et al., 2009) | Energy consumption accounts for ~18 % of the total cost | Chemical such as chlorine, chlorine dioxide, permanganate, oxygen and ozone are required as oxidants | Not required | Capital cost is about \$0.01/gpd. Operation and maintenance cost are approximately \$0.01/bbl. |
| Electro & Chemical Coagulation | For EC, 70% of turbidity and an average of 63% of TOC, For CC, 80% removal of turbidity (Permian Basin Case Study) (Rodriguez et al., 2019) | 0.36-0.4 kW/m$^3$ | Aluminum sulphate and ferric chloride | | \$0.44/m$^3$ (for 63% removal of turbidity with Al electrode) & \$0.26/m$^3$ for $Al_2(SO_4)_3 \cdot 18H_2O$ and \$0.37 for $FeCl_3 \cdot 6H_2O$ respectively |
| Ion Exchange | Nickel and Vanadium removal efficiency up to 98% (Al-Jaser et al., 2018), Combined ion exchange-nanofiltration process, chloride removal efficiency 54– | Uses electrical energy. Energy requirements only include pumping costs, Typically 0.07 kWh/bbl assuming a 200 gpm flow rate, 5m pumping head | Regenerant solution may be $H_2SO_4$, NaOH, HCl or $Na_2CO_3$. $H_2O_2$ or NaOCl cleaning solutions may be used to limit fouling | Pre-treatment is necessary to remove suspended solids, scaling mineral and oxidized metals. Product water may require remineralization of pH stabilization | Cost for IX resin varies between \$0.08 and \$0.11/bbl at 5bbl per minute and \$0.04–\$0.07/bbl at 21bbl per minute. Operating costs account for 70% of the total cost at lower flow rate. At 21 bbl per minute operating costs increase to ~80% |

| | | | | | |
|---|---|---|---|---|---|
| | 59% (Hilal et al., 2015) | | | | |
| NF | Excellent oil removal (~100%) and divalent ion retention (~75% for $Ca^{2+}$ and up to ~80% for $SO_4^{2-}$) (Vigra et.al., 2019) | Approximately 0.08 kWh/bbl to power its high-pressure power pumps | Caustic and scale inhibitors are required to prevent fouling. NaOH, $H_2O_2$, $Na_2SO_4$, HCl or $Na_4EDTA$ are required for cleaning the system | Extensive pre-treatment is required to prevent fouling of the membrane. Product water may require remineralization to restore SAR values | Capital cost ranges from $35 to $170/bpd, operating cost is ~$0.03/bbl<br>Total cost= $0.8337-$4.0407)/gallon |

Table 2: Summary of treatment technologies for various reuse options

| Technologies | Post Treatment Option | Product | Reuse Option |
|---|---|---|---|
| ED/EDR | RO-EDR hybrid technologies | Direct effluent from treatment | Reuse in cooling towers |
| Chemical Oxidation | Biotreatment with microalgae | Post-treated effluent | Surface discharge |
| EC and CC | After coagulation, media filtration is able to achieve further turbidity removal: up to 97% for walnut shell, 95% for new GAC, and 94% for biochar | Clean brine | Onsite reuse in fracking operation |
| Ion Exchange | Not required (Zeng et al., 2007) | Direct effluent from treatment | Reuse in blowdown boiler |
| NF | Implementation of a nanofiltration system in a conventional Steam-assisted-gravity-drainage (SAGD) plant (Hurwitz et al., 2015) | Direct effluent from plant | Reuse in blowdown boiler |

## 2.2. Environmental Assessments

### 2.2.1. Determining Reuse Feasibility Factors

Since PW exists on the surface, cost-effective and eco-friendly methods for its reclamation are better rather than underground disposal. Various factors dictate the feasibility of beneficial reuse in different contexts.

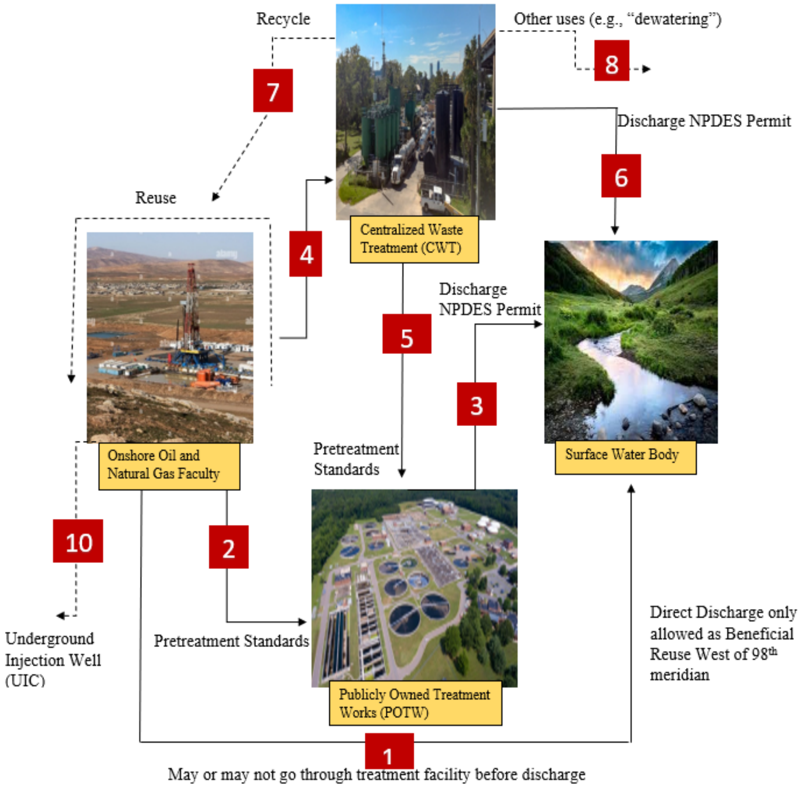


Figure 4: Options for produced water management. (Source: After American Petroleum Institute [modified]). This figure presents the range of alternate options for managing produced water.

Figure 4 illustrates the range of alternate options for managing produced water. Options 1 through 6 show some form of discharge to surface waters, either directly or after treatment in a wastewater treatment facility or a centralized industrial wastewater treatment plant. Produced water can be used again in the oil and gas process without treatment (Option 9) or after treatment (Option 7). Produced water can also be put to other use (Option 8) after treatment. Option 10 shows produced water directed to injection wells.

The perfect utilization of PW for particular uses depends on its quality. A key aspect of water quality is the practicality and expense of treating PW to meet the desired standards for its intended use. The quality of PW is highly variable depending on its source, making it essential to thoroughly analyze its constituents and their quantity for reuse. This involves assessing the potential health and environmental risks associated with releasing these constituents, establishing quality standards necessary to render the produced water fit for purpose and, weighing the costs, benefits, and risks entailed in achieving those standards. Water volumes and longevity also matter. Longevity of supply is particularly crucial when advocating for beneficial reuse beyond the scope of the oil and gas sector. Moreover, the reuse may be constrained by logistical and transportation expenses. The treatment facilities and cost associated with the overall procedure including transportation are the important factors. Transportation costs can be quite high. For instance, the expenses for trucking a typical load from tank battery to salt well disposal (SWD) can range from \$1 to \$3 per barrel. In addition, construction expenses associated with permanent pipelines are typically \$1.45 million per mile on average depending upon pipe size, terrain, right of way costs and others (Produced water report, Ground Water Protection Council, 2019 [Groundwater-report-2019-Produced Water Full Report - Digital Use.pdf])

### 2.2.2. Chemical Assessments

Another consideration is the chemicals that are required for each operation. The data were collected from U.S.EPA and New Jersey Department of Health's hazardous fact sheet. The chemicals used in each operation have different hazard levels. The hazard data are categorized as hazard levels, flammability, reactivity etc. Other parameters are exposure limits, health effects, and the effect of their leakage on the environment. To run, ED/EDR needs EDTA, which is a miscellaneous material having hazard class 9, doesn't burn itself, and may cause several problems to the eye, skin, and inhalation. Most importantly, its leakage may cause serious issues to aquatic organisms. Chemical oxidation requires chlorine, chlorine dioxide [$Cl(OH)_2$], potassium permanganate, and ozone. All of these chemicals have different characteristics. Chlorine is a poisonous gas, and its leakage is harmful to the environment. The other three chemical hazard classes have not been found. However, they should be disposed of as hazardous waste. EC and CC require aluminum sulfate ($Al_2SO_4$) and ferric chloride ($FeCl_3$). $Al_2SO_4$ is an environmentally hazardous material, class-9. It is harmful to aquatic life especially to fish. $FeCl_3$ is not that harmful. Ion exchange needs sulfuric acid ($H_2SO_4$), sodium hydroxide (NaOH), and hydrochloric acid (HCl). Both $H_2SO_4$ and NaOH have hazard class 8. HCl has hazard class-2.3. All of them are harmful to aquatic life. NF requires NaOH, HCl, hydrogen peroxide ($H_2O_2$), and sodium sulfate ($Na_2SO_4$). $H_2O_2$ has hazard class 5.1 and should be kept out of confined spaces such as sewers because of the possibility of an explosion and $Na_2SO_4$ has not been listed as a hazardous substance.

Table 3: Chemical assessments

| Chemical Assessments | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Technologies** | **Chemicals** | **Hazard Data** | | | **Exposure Limits** | **Health Effect** | **Spill/Leaks** |
| ED/EDR | EDTA | Hazard Rating | Fire Hazards | Reactivity | PAC-1= 125 mg/m$^3$<br>PAC-2=150 mg/m$^3$<br>PAC-3= 150 mg/m$^3$ | Eye- Irritation<br>Skin- Irritation and rash<br>Inhalation-Nose and throat irritation with coughing and wheezing | Harmful to aquatic organisms |
| | | 1-Health<br>0-Fire<br>0-Reactivity<br>Hazard Class-9 Miscellaneous Hazardous Material | Itself doesn't burn | Reacts violently with Lead Oxide. It is not compatible with oxidizing agents | | | |
| Chemical Oxidation | Chlorine $Cl_2$ | 4-Health<br>0-Fire<br>0-Reactivity<br>Hazard Class-2.3 (Poison Gas) | Nonflammable gas | Strong Oxidizer. Reacts with water to form acid solution | OSHA- 1 ppm Ceiling<br>NIOSH- 0.5ppm 15-minute Ceiling<br>ACGIH- 0.5 ppm 8-hr, 1 ppm STEL<br>IDLH Level-10 ppm<br>ERPG1- 1 ppm<br>ERPG1- 2 ppm<br>ERPG3- 20 ppm | Eyes- Irritation, burns, and possible eye damage<br>Skin: Irritation, burns. Liquid can cause frostbite<br>Acute- Nose, throat, lung irritation, coughing (Pulmonary edema), headache, nausea, vomiting<br>Chronic- Cancer tested (not classifiable), Asthma with shortness of breath, wheezing, coughing and/or chest tightness.<br>Damage to teeth, skin blisters and hoarseness | Toxic to aquatic organisms |
| | Chlorine Dioxide $ClO_2$ | Not Found-Health<br>4-Fire | Highly flammable. Dangerous fire | Highly Reactive. A powerful oxidizer | OSHA- 0.1 ppm averaged over an 8-hour workshift | Eyes- Irritation, watery eyes and seeing halos around lights. | It should be disposed as a hazardous |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | 3-Reactivity Hazard Class-5.1 (Oxidizer) | and explosion hazard. Explosive at concentrations over 10% and can be ignited by almost any form of energy, including SUNLIGHT, HEAT or SPARKS. Containers may explode in fire | and explodes on contact with Carbon monoxide, hydrocarbons, amines, mercury, organic materials, potassium hydroxide, phosphorus, chlorine, sulfur, heat, metals and alcohols | NIOSH: 0.1 ppm averaged over a 10-hour workshift and<br>0.3 ppm not to be exceeded during any 15-minute work period<br>ACGIH: 0.1 ppm averaged over an 8-hour workshift<br>0.3 ppm as a STEL | Acute- Nose and throat irritation causing coughing and wheezing<br>Lung Irritation, coughing and/or shortness of breath. Higher exposures can cause a build-up of fluid in lungs (Pulmonary edema) | waste.<br>Transportation of pure Chlorine Dioxide is forbidden by DOT |
| | Potassium Permanganate $KMnO_4$ | Not Found- Health<br>Not Found- Fire<br>Not found- Reactivity Hazard Class- Not found | May ignite combustibles (wood, paper and oil) | In contact with certain sulfoxides; aldehydes; strong acids; amines; or glycols may result in fires. It is not compatible with strong bases | OSHA- The legal airborne permissible exposure limit is 5 mg/m3, not to be exceeded at any time<br>NIOSH- The recommended airborne exposure limit is 1 mg/m$^3$ averaged over 10-hour workshift and 3 mg/m$^3$ not to be exceeded during any 15 minutes work period.<br>ACGIH- The recommended airborne exposure limit is 0.03 | Eyes- Irritation, burn and possible eye damage<br>Acute- Breathing $KMnO_4$ can irritate the nose and throat, lungs causing coughing and/or shortness of breath. Higher exposure may cause a build-up of fluid in the lungs (pulmonary edema)<br>Reproductive hazard- It may decrease fertility | It should be disposed as a hazardous waste |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | mg/m$^3$ (as the respirable fraction) averaged over 8-hour workshift | | |
| | Ozone<br>$O_3$ | Not Found- Health<br>Not Found- Fire<br>Not found- Reactivity<br>Hazard Class- Not found | Container may explode in fire | Not available | OSHA- 0.1 ppm averaged over an 8-hour workshift<br>NIOSH- 0.1 ppm, which should not exceed anytime<br>ACGIH- 0.05 ppm, heavy work; 0.08 ppm, moderate work; 0.1 ppm, light work; and workloads of less than 2 hours, 0.20 ppm; averaged over an 8-hour workshift | Eyes- Liquified ozone can cause irritation and severe burns<br>Skin- Liquified ozone can cause irritation and severe burns<br>Acute- Can irritate nose and throat. Higher exposure to ozone can cause headache, upset stomach, vomiting, and plain or tightness in the chest. Breathing ozone can irritate the lungs causing coughing and/or shortness of breath.<br>Cancer- It may cause cancer of the lungs. | It should be contained and disposed as a hazardous waste |
| Electro and Chemical Coagulation | Aluminum Sulfate<br>$Al_2SO_4$ | 2-Health<br>0-Fire<br>0-Reactivity<br>Hazard Class-9 (Environmentally hazardous material) | Itself doesn't burn | Reacts with water; moisture; strong bases; ammonia; and amines. It is corrosive to metals in the presence of water and moisture | NIOSH- 2 mg/m$^3$, 10-hr TWA (as Aluminum, soluble salts)<br>ACGIH- 1 mg/m$^3$, 8-hr TWA (as Aluminum metal respirable fraction)<br>The Protective Action Criteria values are<br>PAC-1=38 mg/m$^3$<br>PAC-2=64 mg/m$^3$<br>PAC-3=380 mg/m$^3$ | Eyes- Irritation<br>Skin- Irritation with rash and burning feeling<br>Inhalation-Nose, throat and lung irritation with coughing, wheezing and shortness of breath | It may be hazardous to the environment, especially to fish |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ferric Chloride $FeCl_3$ | Not Found-Health<br>0-Fire<br>0-Reactivity<br>Hazard Class-Not Available | Itself doesn't burn | React with water to form corrosive Hydrogen Chloride gas and contact with metals may form flammable hydrogen gas. It is not compatible with strong bases; ethylene oxide; oxidizing agents; sulfates and halocarbons | NIOSH- 1 mg/m$^3$ averaged over a 10-hour workshift.<br>ACGIH- 1 mg/m$^3$ averaged over an 8-hour workshift | Eyes-Severely irritate and burn. Prolonged contact can cause discoloration of the eyes.<br>Skin- Severely irritate and burn.<br>Acute- Can irritate nose, throat and lungs causing tightness in the chest and lungs and /or difficulty in breathing | It should be contained and disposed as a hazardous waste |
| Ion Exchange | $H_2SO_4$ | 3-Health<br>0-Fire<br>2-Reactivity<br>Hazard Class- 8 (Corrosive) | Itself doesn't burn. It is not combustible, but it is a strong oxidizer that enhances the combustion of other substances | It reacts violently with alcohol and water to release heat as well as react violently and explosively with organic materials; combustibles, strong bases and oxidizing agents. It is not compatible with strong acids. | OSHA- 1 mg/m$^3$, 8-hr TWA<br>NIOSH- 1 mg/m$^3$, 10-hr TWA<br>ACGIH- 0.2 mg/m$^3$, 8-hr TWA<br>IDLH-15 mg/m$^3$<br>ERPG-1=2 mg/m$^3$<br>ERPG-2=10 mg/m$^3$<br>ERPG-3=120 mg/m$^3$ | Eyes- Severe irritation and burns<br>Skin- Severe irritation and burns<br>Inhalation-Nose, throat and lung irritation with coughing and severe shortness of breath (Pulmonary edema)<br>Headache, nausea, vomiting.<br>Chronic- Strong/ Inorganic acid mists containing sulfuric acid cause cancer of the larynx in humans | Harmful to aquatic organisms |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | NaOH | 3-Health<br>0-Fire<br>2-Reactivity<br>Hazard Class- 8 (Corrosive) | Itself doesn’t burn | Reacts with strong acids; water and moisture to form flammable and explosive hydrogen gas. It is not compatible with oxidizing agents. | OSHA- 2 mg/m$^3$, 8-hr TWA<br>NIOSH- 2 mg/m$^3$, Ceiling<br>ACGIH- 2 mg/m$^3$, Ceiling<br>IDLH- 10 mg/m$^3$<br>The protective Criteria values are<br>PAC- 0.5 mg/m$^3$<br>PAC-25 mg/m$^3$<br>PAC3=50 mg/m$^3$ | Eyes- Severe irritation and burns and possible eye damage<br>Skin- Severe irritation and burns<br>Inhalation-Nose, throat and lung irritation with coughing and severe shortness of breath (Pulmonary edema) | It is hazardous to the environment, especially water organisms |
| | HCl | 3-Health<br>0-Fire<br>1-Reactivity<br>Hazard Class- 2.3 (Toxic Gas) (Anhydrous)<br>8 (Corrosive) (Solution) | Itself doesn’t burn | Reacts explosively with alcohols; hydrogen cyanide, potassium permanganate etc. It also reacts with oxidizing agents. | OSHA- 5 ppm, Ceiling<br>NIOSH-5 ppm, Ceiling<br>ACGIH- 2 ppm, Ceiling<br>IDLH- 50 ppm<br>The protective Criteria values are<br>PAC- 1.8 ppm<br>PAC-22 ppm<br>PAC3-100 ppm | Eyes- Severe irritation and burns and possible eye damage<br>Skin- Severe irritation and burns<br>Contact with liquid causes frostbite<br>Inhalation-Nose, throat and lung irritation with coughing and severe shortness of breath (Pulmonary edema) | It should be covered with dry lime, sand or soda ash and placed into sealed containers for disposal |
| NF | NaOH | 3-Health<br>0-Fire<br>2-Reactivity<br>Hazard Class- 8 (Corrosive) | Itself doesn’t burn | Reacts with strong acids; water and moisture to form flammable and explosive hydrogen gas. It is not compatible | OSHA- 2 mg/m$^3$, 8-hr TWA<br>NIOSH- 2 mg/m$^3$, Ceiling<br>ACGIH- 2 mg/m$^3$, Ceiling<br>IDLH- 10mg/m$^3$<br>The protective Criteria values are<br>PAC-1= 0.5 mg/m$^3$ | Eyes- Severe irritation and burns and possible eye damage<br>Skin- Severe irritation and burns<br>Inhalation-Nose, throat and lung irritation with coughing and severe shortness of breath (Pulmonary edema) | It is hazardous to the environment, especially water organisms |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | with oxidizing agents. | PAC-2=25 mg/m$^3$<br>PAC-3=50 mg/m$^3$ | | |
| | $H_2O_2$ | 3-Health<br>0-Fire<br>3-Reactivity<br>Hazard Class- 5.1 (Oxidizer) | It may ignite combustibles (wood, paper, and oil) | Concentrated solutions can decompose violently if trace impurities are present. It reacts violently with finely divided metals; reducing agents; combustibles; strong bases; oxidizing agents and metals | OSHA- 1 ppm, 8-hr TWA<br>NIOSH-1 ppm, 10-hr TWA<br>ACGIH- 1 ppm, 8-hr TWA<br>IDLH- 75 ppm<br>The protective Criteria values are<br>PAC-1=10 mg/m$^3$<br>PAC-2=50 mg/m$^3$<br>PAC-3=100mg/m$^3$ | Eyes- Irritation, burns and eye damage<br>Skin- Irritation, burns, skin rash, redness and blisters<br>Inhalation-Nose, throat and lung irritation with coughing and severe shortness of breath (Pulmonary edema) | It should be kept out of confined spaces such as sewers because of the possibility of an explosion |
| | $Na_2SO_4$ | Not listed as hazardous chemical | | | | | |
| | HCl | 3-Health<br>0-Fire<br>1-Reactivity<br>Hazard Class- 2.3 (Toxic Gas) (Anhydrous)<br>8 (Corrosive) (Solution) | Itself doesn't burn | Reacts explosively with alcohols; hydrogen cyanide, potassium permanganate etc. It also reacts with oxidizing agents. | OSHA- 5 ppm, Ceiling<br>NIOSH-5, Ceiling<br>ACGIH- 2 ppm, Ceiling<br>IDLH- 50 ppm<br>The protective Criteria values are<br>PAC- 1.8 ppm<br>PAC-22 ppm<br>PAC3-100 ppm | Eyes- Severe irritation and burns and possible eye damage<br>Skin- Severe irritation and burns<br>Contact with liquid causes frostbite<br>Inhalation-Nose, throat and lung irritation with coughing and severe shortness of breath (Pulmonary edema) | It should be covered with dry lime, sand or soda ash and placed into sealed containers for disposal |
| Here, OSHA- The Occupational Safety and Health Administration, which adopts and enforces health and safety standards. | | | | | | | |

NIOSH- The National Institute for Occupational Safety and Health. It tests equipment, evaluates and approves respirators, conducts studies of workplace hazards, and proposes standards to OSHA

ACGIH- The American Conference of Governmental Industrial Hygienists. It recommends upper limits (TLVs) for exposure to workplace chemicals

### 2.2.3 Electricity Generation and its impact on the environment

The quantity of $CO_2$ emission from the electric power generation industry depends on the source type of energy as well as the efficiency of power plants. Therefore, $CO_2$ emissions from electric power plants fluctuate according to the fuel supplied to the power grid during that time. The U.S. Energy Information Administration (EIA) tracks and publishes estimates of $CO_2$ emissions from electricity production on a monthly and yearly basis. In the US, around 4.23 trillion kilowatt-hours (kWh) of electricity have been generated, and ~1.65 billion metric tons of $CO_2$ have been emitted in 2022. $CO_2$ emissions from electricity generation using different fuel sources are about 0.86 pounds per kWh.

The utility-scale power plants that utilized coal, natural gas, and petroleum fuels were contributed to around 60% of total annual U.S. utility scale electricity net generation in 2022. Whereas, they accounted for 99% of $CO_2$ emissions linked with utility -scale electric power production. The remaining 1% of $CO_2$ emissions stemmed from other fossil fuels and gases alongside other geothermal power plants. The Energy Information Administration (EIA) regards electricity production from solar, biomass, hydro, and wind as carbon neutral (U.S. Energy-Related Carbon Di-Oxide Emissions, 2023 [U.S. Energy Information Administration - EIA - Independent Statistics and Analysis])

Table 4 shows data on total annual electricity net production and $CO_2$ emissions at utility-scale electric power plants as well as a $CO_2$ emission factor (lb of $CO_2$/kWh) for coal, natural gas and petroleum, and the average of all energy sources. The amount of $CO_2$ emission for particular power grid may differ from the factors in the table. Table 5 presents the possible $CO_2$ emissions from five technologies discussed.

Table 4: U.S. electricity generation and resulting CO2 emissions by fuel in 2022 (Source: U.S. Energy-Related Carbon Di-Oxide Emissions, 2023)

| **Source** | **Electricity Generation Million kWh** | **$CO_2$ Emissions Million Metric Tons** | **Million Short Tons** | **Pounds Per kWh** |
|---|---|---|---|---|
| Coal | 831,512 | 868 | 957 | 2.30 |
| Natural gas | 1687,067 | 743 | 819 | 0.97 |
| Petroleum | 22,931 | 25 | 27 | 2.38 |
| All Energy Sources (Including Other Minor Sources) | 4230,672 | 1,650 | 1,819 | 0.86 |

Table 5: Possible $CO_2$ emission from five technologies

| **Technologies** | **Electric Energy Consumption** | **$CO_2$ Emission/lb (0.86 Pounds per kWh)** |
|---|---|---|
| EDR/ED | 0.14-0.20 kWh/lb (154 kWh/$m^3$) | 132.44 |
| Chemical Oxidation (Anodic Oxidation) | 38 - 46 kWh /$m^3$ (BDD and $PbO_2$ electrodes respectively) | 32-39.56 |
| Electro and Chemical Coagulation | 0.36-0.4 kWh/$m^3$ | 0.309-0.344 |
| Ion Exchange | 0.07 kWh/bbl (0.44 kWh/$m^3$) | 0.37 |
| NF | 0.08 kWh/bbl (0.50 kWh/$m^3$) | 0.43 |

# 3. Methodology

## 3.1. Technical Assessments

Technology evaluation for PW treatment is very difficult as different technologies can effectively remove different types of constituents. For instance, ED can effectively remove anions, cations and alkalinity. Coagulation process can eliminate organic and inorganic pollutants, including suspended particles, phosphates, and insoluble free hydrocarbons. Compared to other treatment processes, coagulation is a cost-effective and efficient method for removing color, COD and turbidity (Hao et al., 2014). Meanwhile, advanced oxidation processes can achieve full mineralization of oxidizable, non-biodegradable organic pollutants (Esplugas et al., 1997). Therefore, the technological evaluation highly depends on what is the ultimate goal of treating PW. Since, this research aims to focus on Permian Basin PW, the hybrid technology consists of electrocoagulation-microfiltration-membrane distillation and another consists of hydrocyclone, coagulation/flocculation, MVC, membrane bioreactor, and UV/$H_2O_2$ are the most efficient technologies as the effluent from these technologies can be used as irrigation, livestock feeding, indirect potable water, etc. Among the simple technologies, EC and CC are the most efficient technologies as they meet up on-site reuse standards.

## 3.2. Economical Assessments

The economic assessments include capital costs and operational expenses. Operational costs include raw materials like chemicals, energy, apparatus maintenance, and labor costs. A general overview of the estimated costs has been presented. No attempt was made to ascribe economic factors to these technologies since costs will vary from location to location and may be depend on commercial configurations and innovations. A general cost estimate has been presented for each of the technologies. Again, these costs are a general budget for the treatment technologies not for those specific case studies that have been discussed. Since the PW from Permian Basin is highly contaminated, these costs are not a proper cost estimate for Permian Basin's PW treatment technologies for beneficial reuse. Firstly, a series of operations need a high amount of money for the apparatus setup. Secondly, specific maintenance costs are required in each step. Here, the EC and CC are the specific case studies that have treated PW from Permian Basin produced water samples and successfully treated water for onsite reuse purposes. EC and CC are the most effective technology among the five to treat Permian Basin PW even if the cost is higher (EC: \$0.44/$m^3$ [for 63% removal of turbidity] and [CC: \$0.26/$m^3$ for $Al_2(SO_4)_3 \cdot 18H_2O$ and \$0.37 for $FeCl_3 \cdot 6H_2O$ respectively]) than other technologies.

## 3.3. Environmental Assessments

The environmental assessment in this research has been evaluated mainly in terms of beneficial reuse purposes. That means that any technology can successfully treat PW up to the standard of any type of beneficial reuse for example onsite reuse, irrigation, potable water or livestock feeding. However, some technologies can meet the target, but their power consumption, and chemical consumption may have a considerable negative impact on the environment. For instance, if a technology needs high power for its operation, such power generation may pollute the environment with high carbon or other air emission. Moreover, some chemicals are highly hazardous and may have strict exposure limits to human beings and discharge on the environment may cause serious threat to the environment or ecosystem chain. Therefore, these technologies may not be termed as environment-friendly technologies. The very five technologies that have been discussed here, need chemicals for their operation. Such chemicals have almost the same level of hazards and impacts on the environment and human exposure limits. These are shown in Table 3.

The ED/EDR process needs more power for its operation, and the potential $CO_2$ emission is 132.44 lb. Whereas, possible $CO_2$ emission from EC and CC processes 0.309-0.344 lb. Therefore, EC and CC are the most environmentally friendly technologies.

# 4. Result and Discussion

## 4.1. Data Screening

According to the five case studies discussed, it has been observed that utilizing the PW in particular sectors requires extensive pre- and post-treatments. In Texas, the most common practice to manage PW is the injection into Class II wells. However, onsite reuse is the best reuse option since it reduces fresh water consumption in the operation as well as free from trucking, pipelines, associated manpower, air emissions from container vehicles, leakage uncertainties, safety issues, traffic problems etc. To evaluate the efficiencies of the five technologies to treat PW of the Permian Basin, the water quality parameters have been assumed to be in the 75th percentile of Table 7 and Table 8. According to the removal efficiencies of five technologies, a mathematical calculation has been done to observe if that technology can remove the pollutants of PW from Permian basin up to any of the reuse criteria. The Standards for reuse in irrigation and for livestock have been provided by the US Department of Agriculture, Natural Resources Conservation Service (Table: 6). The expenditure information of the technologies has been collected from journals, literature, reports, and Made-in-Chaina.com (manufacturers, suppliers in China). The economic evaluation has been done directly by comparing the overall costs of the technologies. The overall cost includes capital cost and operation cost. Capital costs include chemical or raw material costs and apparatus setup cost. The operation cost includes energy costs, labor costs, and maintenance costs. Other costs, like equipment failure, uncertainty, transportation, after-treatment waste management costs, are not a part of this research.

The environmental data has been collected from U.S.EPA reports. Chemical assessments have been done directly comparing the chemical's impact on the environment which is collected from

State of New Jersey department of health and safety, right to know hazardous substance fact sheets.

Table 6: Standards for water reuse for drinking, irrigation and livestock purposes (Source: U.S.EPA)

| **Component** | **Drinking($g/m^3$)** | **Irrigation($g/m^3$)** | **Livestock($g/m^3$)** |
|---|---|---|---|
| $Li^+$ | - | 2500 | - |
| $K^+$ | - | - | - |
| $Na^+$ | 200 | Based on SAR | 2000 |
| $NH_3$ | 1.5 | - | - |
| $Ca^{2+}$ | - | Based on SAR | - |
| $Mg^{2+}$ | - | Based on SAR | 2000 |
| $Br^-$ | - | - | - |
| $Cl^-$ | 250 | - | 1500 |
| $HCO_3^-$ | - | - | - |
| $SO4_2^-$ | 250 | - | 1500 |
| TDS | 500 | 2000 | 5000 |
| Conductivity(dS/m) | - | 2.5 | 1.5-5 |
| Sodium adsorption ratio (SAR) | - | 0-6 | - |

The characteristics of PW collected from the Permian Basin are summarized below (Jiang et al., 2022)

Table 7: Statistical results of general quality parameters of the total 45 PW samples

| **Compo-nent** | **Unit** | **Mean** | **Max** | **Min** | **25th Per-centile** | **50th Per-centile** | **75th Per-centile** |
|---|---|---|---|---|---|---|---|
| Alkalinity | mg/L as $CaCO_3$ | 272 | 870 | 100 | 128 | 207 | 336 |
| Ammonia | mg/L | 432 | 750 | 320 | 330 | 400 | 495 |
| COD | mg/L | 1626 | 3100 | 930 | 1250 | 1400 | 1950 |
| pH | SU | 6.6 | 8.1 | 3.9 | 6.3 | 6.7 | 7.0 |
| TDS | mg/L | 128,641 | 201,474 | 100,830 | 113,441 | 122,280 | 134,525 |
| TOC | mg/L | 103.5 | 248.1 | 2.4 | 28 | 90.6 | 173.3 |
| TSS | mg/L | 342.9 | 790 | 85 | 142.5 | 375 | 422.5 |
| Turbidity | NTU | 116.4 | 200 | 23 | 36 | 110 | 200 |
| MBAS | mg/L | 1.10 | 2.1 | 0.047 | 0.92 | 0.97 | 1.33 |

Table 8: Statistical results of comprehensive elements analyses of the 46 PW samples

| **Component** | **Unit** | **Mean** | **Max** | **Min** | **25th Per-centile** | **50th Per-centile** | **75th Per-centile** |
|---|---|---|---|---|---|---|---|
| Cations | | | | | | | |
| Aluminum | mg/L | 1.09 | 3.95 | 0.37 | 0.63 | 0.76 | 1.25 |
| Arsenic | mg/L | 3.17 | 6.04 | 1.62 | 1.74 | 2.64 | 4.61 |
| Barium | mg/L | 2.21 | 12.00 | 0.10 | 0.45 | 1.69 | 3.00 |
| Beryllium | mg/L | 0.03 | 0.04 | 0.01 | 0.01 | 0.03 | 0.04 |
| Bismuth | mg/L | 1.02 | 1.77 | 0.71 | 0.72 | 0.81 | 1.55 |
| Boron | mg/L | 42.34 | 76.50 | 17.20 | 33.29 | 40.65 | 51.03 |
| Cadmium | mg/L | 0.47 | 0.81 | 0.04 | 0.08 | 0.63 | 0.77 |
| Calcium | mg/L | 3821 | 8186 | 880 | 1705 | 3531 | 5744 |
| Chromium | µg/L | 1.7 | 2.2 | 1.3 | 1.3 | 1.6 | 2.2 |
| Cobalt | µg/L | 7.7 | 7.8 | 7.5 | 7.5 | 7.7 | 7.8 |
| Copper | mg/L | 0.65 | 1.46 | 0.24 | 0.24 | 0.45 | 1.26 |
| Ferrous iron | mg/L | 3.09 | 6.70 | 0.57 | 0.73 | 3.00 | 5.50 |
| Iron | mg/L | 19.35 | 65.20 | 0.50 | 4.60 | 14.00 | 25.70 |
| Lithium | mg/L | 22.39 | 52.28 | 11.74 | 20.00 | 21.02 | 23.40 |
| Magnesium | mg/L | 745.0 | 1877 | 295.3 | 472.2 | 621.3 | 959.1 |
| Manganese | µg/L | 488 | 1239 | 10 | 116 | 472 | 781 |
| Molybdenum | mg/L | 0.21 | 0.38 | 0.10 | 0.11 | 0.18 | 0.35 |
| Potassium | mg/L | 923 | 3637 | 222 | 449 | 808 | 1171 |
| Selenium | mg/L | 2.5 | 2.5 | 2.5 | n/a | 2.5 | n/a |
| Silica | mg/L | 107.7 | 195.4 | 4.0 | 29.2 | 115.7 | 178.2 |
| Sodium | mg/L | 40,896 | 68,985 | 25,080 | 37,000 | 39,673 | 42,967 |
| Strontium | mg/L | 449.9 | 1404 | 28.9 | 116.4 | 325.3 | 816.5 |
| Thallium | mg/L | 0.83 | 0.84 | 0.82 | n/a | 0.83 | n/a |
| Thorium | mg/L | 0.048 | 0.054 | 0.035 | 0.035 | 0.054 | 0.054 |
| Uranium | mg/L | 0.303 | 0.5 | 0.19 | 0.19 | 0.22 | 0.5 |
| Vanadium | µg/L | 79.6 | 94.5 | 61.4 | 61.4 | 83.0 | 94.5 |
| Zinc | mg/L | 1.14 | 1.81 | 0.17 | 0.17 | 1.45 | 1.81 |
| Anions | | | | | | | |
| Sulfate | mg/L | 496 | 965 | 151 | 243 | 510 | 690 |
| Phosphorous as P | mg/L | 8.5 | 36.0 | 1.7 | 2.5 | 6.4 | 8.9 |
| Nitrate as N | mg/L | n/a | 16 | n/a | n/a | n/a | n/a |
| Iodide | mg/L | 88 | 94 | 77 | 82 | 90 | 94 |
| Chlorine | mg/L | 78,648 | 120,200 | 57,543 | 69,269 | 75,658 | 86,979 |
| Bromide | mg/L | 431 | 960 | 95 | 238 | 289 | 608 |
| Radionuclides | | | | | | | |
| Gross Alpha | pCi/L | 1105.6 | 1630 | 660 | 745 | 863 | 1630 |
| Gross Beta | pCi/L | 874.6 | 1230 | 456 | 748 | 889 | 1050 |
| Radium-226 | pCi/L | 237.6 | 970.0 | 0.7 | 19.1 | 72.8 | 415.5 |
| Radium-228 | pCi/L | 231.7 | 576.0 | 2.6 | 137.5 | 273.0 | 285.0 |
| Uranium-234 | pCi/L | 0.33 | 0.76 | 0.20 | 0.24 | 0.24 | 0.24 |
| Uranium-238 | pCi/L | 0.17 | 0.17 | 0.17 | n/a | n/a | n/a |
| Thorium-228 | pCi/L | 21.5 | 52.1 | 3.4 | 3.7 | 21.5 | 30.5 |
| Thorium-230 | pCi/L | 0.22 | 0.39 | 0.09 | 0.17 | 0.21 | 0.24 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Polonium-210 | pCi/L | 3.28 | 5.38 | 1.75 | 2.24 | 2.72 | 4.05 |
| Plutonium-238 | pCi/L | 0.17 | 0.17 | 0.17 | n/a | n/a | n/a |

## 4.2. Technical Assessments of Five Technologies

ED/EDR system mainly removes ions, and the ion removal range is 84-91% for the coagulation-ED hybrid process and 90% for the EDR-RO hybrid process. The U.S.EPA report (Table: 6) shows the ions standard for drinking, irrigation and livestock feeding. Among the ions mentioned in the U.S.EPA report, the largest amount of ion (Table: 8) is chloride (86,979 mg/L), and the lowest ion is lithium (23.40 mg/L). Therefore, if the coagulation-ED hybrid process is pursued, then the treated water will contain 7,828 mg/L of chloride ion and 2 mg/L of lithium (after 91% of removal). If the EDR-RO hybrid process is pursued, the treated water will contain 8,698 mg/L of chloride ion and 2.34 mg/L of lithium (after 90% of removal). Therefore, according to U.S.EPA standards, only the quantity of lithium can meet irrigation standards but even with 91% removal of chloride ion, the PW from the Permian basin cannot attain any of the standards.

In the case of the chemical oxidation process, the batch ozone-photocatalytic oxidation ($O_3$/UV/$TiO_2$) process can remove up to 99.9% phenols, 98.2% O&G (oil & grease), 97.2% sulfide, 89.2% COD, and 15% ammonia. From Table 8, the PW of Permian Basin contains COD 1950 mg/L COD and 495 mg/L ammonia. Therefore, after treatment the effluent will contain 214.5 mg/L COD and 420 mg/L ammonia (after 89% and 15% of removal respectively). The U.S.EPA standard report (Table: 6) does not mention COD and ammonia as regulated parameters. Therefore, this technology may not be appropriate for these reuse purposes. In the reference paper (Correa et al., 2010), the raw PW had COD 2,865 mg/L and ammonia was 47.5 mg/L. Therefore, the COD of that sample PW is larger than the PW sample from the Permian basin. However, the amount of ammonia is way more in the sample water from the Permian Basin than the water sample from the reference paper (Correa et al., 2010). According to that reference paper, additional biotreatment is required to meet surface discharge standards. However, for the PW from the Permian basin, even if the amount of COD can meet the standard utilizing the same technology, the amount of ammonia will exceed the limit. Therefore, it may not be a good idea to treat the Permian basin's PW for surface discharge utilizing this technology.

For EC, 70% of turbidity is achieved and an average of 63% is achieved for TOC; For CC, 80% of turbidity is removed. If the 75th percentile is considered from Table:7, then the TDS is 134,525 mg/L, COD is 1,950 mg/L, and turbidity is 200 NTU. According to the reference paper, EC technology utilized in full-scale applications, such as the CleanWave® water treatment mobile device (Halliburton, Houston, TX, USA), can treat up to 26,000 barrels (4100 $m^3$) of produced water per day with a low energy consumption. This equipment can reduce total suspended solids (TSS) by 99% while bringing turbidity to <10 NTU. The TDS range in which the device is completely functional is 100–300,000 mg/L. Moreover, this device is mobile. Therefore, it seems like EC is a good fit technology to deal with PW of the Permian basin.

For ion-exchange technology, a hybrid technology consisting of ultrafiltration, ion exchange and MOX disinfection has been referred. The aim is to reuse the final effluent in cooling towers. In the first stage (UF), the removal efficiencies are TDS at 27%, COD at 47%, and turbidity at 83%. If we consider the water sample from the Permian basin, (TDS is 134,525 mg/L, COD is 1,950 mg/L, turbidity is 200 NTU). After the first stage (after 27% of removal TDS becomes 98,203 mg/L, after 47% of removal COD becomes 1,033.5 mg/L, after 83% removal turbidity becomes 34 NTU) the effluent does not meet any of the reuse sector's criteria (drinking, irrigation, livestock watering, surface discharge or cooling tower). In the second stage (ion exchange), the TDS and turbidity can further reduce to 19,641 mg/L (after 80% of removal), and 11 NTU (after 67% removal), respectively. COD remains the same in this stage. The water quality in this stage also does not meet any of the reuse criteria. In the final stage (MOX disinfection), TDS, COD. and turbidity become 3,928 mg/L (80% of removal), 444 mg/L (57% of removal), and 0.66 NTU (94% of removal), respectively. In the reference paper, the final effluent had TDS 209 mg/L, COD 31.09 mg/L and 0.44 NTU (Hashemi et al., 2019), which met the standard water quality for cooling towers. In that case, the feed water also contained significantly less TDS, COD and turbidity. Therefore, this hybrid system may not be eligible to treat the PW from the Permian basin for reuse in cooling towers. However, the offshore disposal limit is 25 NTU for turbidity and 125 mg/L for COD (Khor et al., 2020). Therefore, the effluent water from this operation may be eligible for offshore disposal.

For NF, a hybrid system (Pretreatment-NF-RO) has been presented, which consists of one or multiple pretreatment stages, and this can significantly reduce the contaminants. The NF stage can remove TDS at 39% (6 bar) and 15.58% (20 bar), with turbidity removal at 99%. In the third stage (RO stage), TDS removal efficiency is 71.4%, and turbidity removal is 99%. The reference paper (Alzahrani et al., 2013) aimed to conduct study to treat PW to reach the drinking water quality regulated by the U.S.EPA and WHO. Therefore, to address drinking water quality, other ions, metals and organic compounds also need to be considered. In that paper, the feed water to NF stage had TDS 823 mg/L and turbidity <1 NTU in 20 bar applied pressure (Alzahrani et al.,2013). Therefore, to deal with PW from the Permian basin, multiple expensive pretreatment will be needed to prepare a feed water for the NF stage to reduce the TDS level similar to the reference paper. Therefore, treating PW of the Permian basin for drinking purposes may not be a good idea. However, this hybrid technology may be pursued to attain minimal standards for well disposal.

### 4.3. Economic Assessments of Five Technologies

The economic evaluation has been done by comparing the overall treatment cost per unit volume of PW. The costs are presented in Table 1. NF needs a high budget to treat PW ($0.833-$4.04/gallon). Whereas, the ED/EDR process needs less budget for all of those five technologies and its cost is $0.15/bbl. The costs of EC and CC are $0.44/m$^3$ (for 63% removal of turbidity with Al electrode) and $0.26/m$^3$ for $Al_2(SO_4)_3 \cdot 18H_2O$ and 0.37 for $FeCl_3 \cdot 6H_2O$ respectively. Among these technologies, EC and CC are technologically efficient as it is successful in treating PW from the Permian basin for reuse purposes even if they are costlier than ED/EDR.

### 4.4 Environmental Assessments of Five Technologies

From Table 3, Table 4 and Table 5, the information has been compared for each technology. In the case of ED/EDR, the effluent water is unable to meet any reuse criteria not even surface discharge criteria. Therefore, any contact of this water with the environment may cause pollution. Moreover, the estimated associated $CO_2$ emission is 132.44 lb. The chemical assessments table (Table: 3) shows that the consumed chemicals are not much different from other chemicals needed for other technologies. For the chemical oxidation process ($O_3$/UV/$TiO_2$), the estimated $CO_2$ emission is 32-39.56 lb. Moreover, the effluent water is not reusable. The chemicals needed for this operation are almost the same as to other. In the case of EC and CC, associated $CO_2$ emission is 0.309-0.344 lb, which is the lowest among all technologies presented here. The most important thing is the effluent water is eligible for on-site reuse. Therefore, there are no other environmental issues associated with these technologies. In the case of the ion exchange process, the estimated $CO_2$ emission is 0.37 lb, which is low. The effluent water is not eligible for reuse. Moreover, the chemicals have almost the same hazardous levels and exposure limit to humans. Associated carbon emission in the case of NF technology is 0.43 lb. The consumed chemicals are not highly hazardous. Most importantly, treated water cannot be used for any beneficial purposes. Therefore, among these five, EC and CC are the most environment-friendly processes.

## 4.5. Case Studies Analysis

### 4.5.1. Pretreatment

Coagulation and flocculation as a pretreatment

If the TDS of the influent water exceeds 40,000 mg/L, a pretreatment is necessary. This can be achieved by coagulation/flocculation, filtration or scale control by adding acid. (Wang et al., 2007). A study examined the effectiveness of the coagulation-flocculation-sedimentation (CFS) process on 14 produced water samples from the Permian Basin. Initially, the samples were analyzed for pH, TSS, TDS zeta potential, turbidity, organic matter, and ion concentrations. Subsequently, a jar test was conducted to pretreat these wastewater samples in a laboratory setting. Ferric sulfate was found to reduce suspended solids by up to 96.6% and turbidity by up to 99%. The use of cationic starch as a flocculant, mainly in combination with ferric sulfate, proved to be an effective method for removing TDS. Additionally, cationic starch was able to further reduce TSS by 3% when used with alum and by 2.37% when used with ferric sulfate (Kaishentayev et al.,2021).

Electrodialysis as a Pretreatment

Electrodialysis experiments were conducted using an Ameridia EUR2B-10 Skid (Sirivedhin et al., 2004). The membrane stack was powered through the anode and cathode by an XHR 40-25 programmable DC power supply. The stack comprised of 10 pairs of active cells, each with a cationic exchange membrane (Neosepta® CMX-SB) and an anionic exchange membrane (Neosepta® AMX-SB). Additionally, two cationic exchange membranes (Neosepta® CMX-SB) were used at the end to prevent contact between the diluate/concentrate and the cathode/anode rinse solutions. Each cell had an active area of 200 $cm^2$, making the total area for the stack 2000 $cm^2$. All electrodialysis experiments were conducted at constant voltage with 3.0, 6.5, and 9.8 V. The electrode rinse solution used in all experiments was a 3,000 $mol/m^3$ $NaNO_3$ solution (Fisher Scientific, Laboratory grade). The TDS concentrations of five samples were Colorado (5,502 mg/L), Texas (4,435 mg/L), Wyoming (5,009 mg/L), Utah (~63,000 mg/L), and Oklahoma (~97,000 mg/L).

The effect of applied voltage on TDS reduction was analyzed. Figures 5A and 5B illustrate the rate of TDS reduction at each voltage setting for the five water samples in both absolute and percentage terms. The results showed that both the absolute and percentage reductions in TDS increased linearly with higher voltages across all feed TDS concentrations. Figure 5A indicates that the rate of TDS reduction per voltage increment varied between waters with low (CO, TX, and WY) and high (UT and OK) TDS concentrations. Specifically, within the studied range, a low TDS waters and 70.9 $g/m^3$ per minute for high TDS waters.

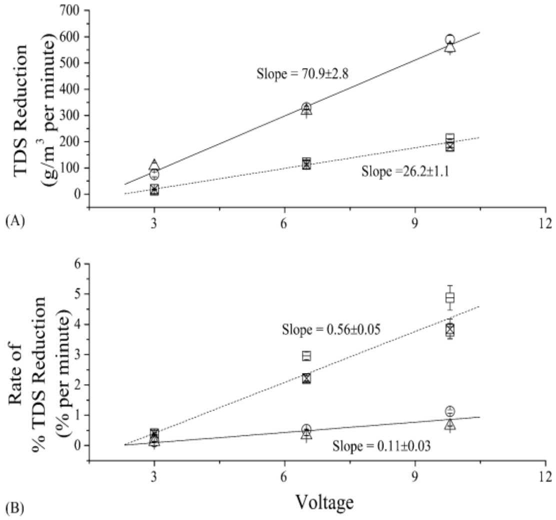


Figure 5: Influence of voltage on (A) absolute and (B) percent TDS reduction from low and high TDS content waters (□) CO, (Ξ) TX, (☒) WY, (O) UT, and (Δ) OK. (-----) low TDS (__) high TDS waters. (Source: Sirivedhin et al., 2004).

Since a linear trend can be observed, long time of operation (120-180 min or more) and > 9.5 V voltage can provide effluent water having TDS and other constituents in such a standard that it can be a feed water for the EDR-RO and ED-UF-MOX process. However, there is no guarantee that this will work due to unknown variables.

### 4.5.2. Proposed Series Treatment Technologies

#### Combined electrocoagulation-microfiltration-membrane distillation

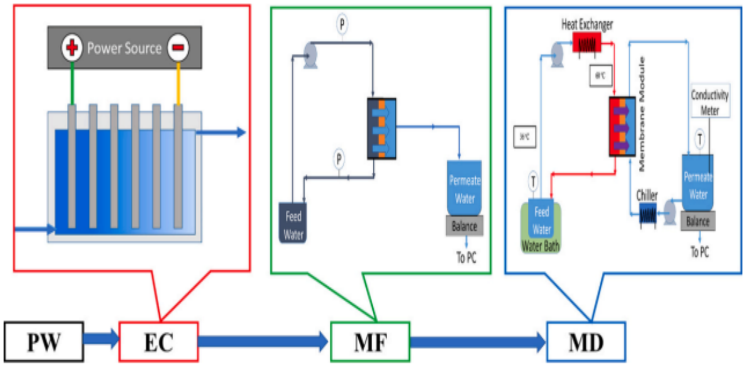


Figure 6: Hybrid process EC-MF-MD. (Source: Jebur et.al., 2021)

An excellent hybrid technology has been designed that can eventually remove all the contaminants significantly. As shown in Figure 6, electrocoagulation followed by microfiltration (MF) had been employed as pretreatment for the wastewater before membrane distillation (MD). In that very experiment the TDS concentration was 245,300 mg/L. After pretreatment the total organic carbon (TOC) decreased from 120 mg/L to 64 mg/L. In the second step, tangential flow MF utilizing a polyethersulfone membrane with 0.1 µm pores was used to isolate particulate matter. In this step, the TOC was further reduced to 44 mg/L. Subsequently, MD was employed to desalinate the effluent of the MF process, resulting in high-quality treated water with a TDS of 56 mg/L and TOC 1 mg (Jebur et.al.,2021).

In the EC step, aluminum electrodes were used. A range of current (1A-9.5 A) and reaction times of 5 to 20 min were observed. The best result was found at 9.5 A and 20 mins of operation period, which shows 48% of TOC removal. For MD, three types of membranes were tested. Among them, the MWCNT PTFE delivered the highest flux and best performance, provided no organic compounds can be adsorbed onto the membrane surface. For a rough estimate, MWCNT

PTFE costs start from $50 to several hundred dollars per square meter, depending on the specific configuration and application requirements. The estimated power cost for 20 minutes operating time with a current of 9.5A is approximately $0.0456.

Table 9: Water quality analysis for PW received from the hydraulic fracturing facility and after each water treatment operation.

| **Parameter** | **Unit** | **PW** | **PW treated by EC** | **PW treated by EC-MF** | **PW treated by EC-MF-MD** |
|---|---|---|---|---|---|
| TDS | mg/L | 245,300 | 238,400 | 239,760 | 56 |
| TOC | mg/L | 120 | 64 | 44 | 1 |
| TSS | mg/L | 131 | 186 | 48 | 1 |
| Turbidity | NTU’s | 6 | 13 | 0.3 | 0.4 |
| pH | - | 6.7 | 3.8 | 3.9 | 7.1 |
| Chloride | mg/L | 156,820 | 160,250 | 166,170 | 5 |
| Sulfate | mg/L | 478 | 419 | 430 | 0 |
| Iron | mg/L | 0.2 | 0.6 | 0.7 | 0 |
| Boron | mg/L | 97 | 87 | 85 | 0 |
| Calcium | mg/L | 30,500 | 30,300 | 31,700 | 1 |
| Magnesium | mg/L | 5454 | 5500 | 5335 | 0 |
| Manganese | mg/L | 0.1 | 0.3 | 0.4 | 0 |
| Nickel | mg/L | 0.2 | 0.4 | 0.4 | 0 |
| Potassium | mg/L | 4331 | 4800 | 4680 | 0.4 |
| Aluminum | mg/L | 0 | 97 | 64 | 0 |
| Sodium | mg/L | 63,600 | 68,600 | 68,100 | 4 |
| Conductivity | µS/cm | 323,400 | 228,000 | 229,000 | 35 |

Hydrocyclone, coagulation/flocculation, MVC, membrane bioreactor, and UV/$H_2O_2$

Another hybrid technology was built by Chen et al., 2023. The diagram of the multi-stage operations has been shown below:

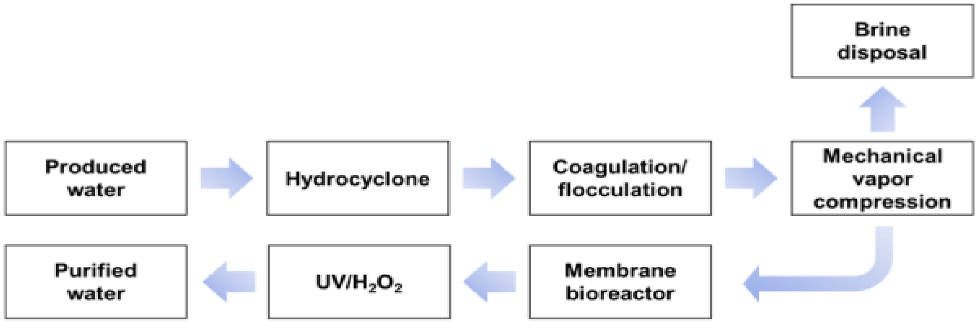


Figure 7: Hydrocyclone, coagulation/flocculation, MVC, membrane bioreactor, and UV/H2O2 are used to remove dispersed oil particles, suspended solids, inorganic constituents, organic constituents, and microorganisms, respectively (Source: Chen et al., 2023)

The methods for treating Permian Basin PW to make it suitable for domestic use, irrigation and livestock watering are illustrated on Figure 7. A hydrocyclone chamber was installed to remove dispersed oil particles. Next, coagulation and flocculation were applied to eliminate both TDS and TSS. Because of high TDS, MVC is preferred for desalination instead of RO. Based on previous studies, the water recovery rate of MVC is 20%-40%. Here, in this experiment, the water recovery by MVC was assumed to be 30%. The brine disposal cost by evaporation is approximately $0.40-0.78/bbl. Afterward, the desalinated water was passed to a membrane bioreactor, effectively removing organic constituents. Finally, UV/$H_2O_2$ were applied for disinfection and microorganism removal.

The overall cost including operation, maintenance, energy, labor and disposal cost of the total operation is about $1.01/bbl.

## 5. Conclusions

Untreated PW is often seen as a large-scale hazardous waste, but with proper management, it can be advantageous for beneficial reuse. Treating PW is crucial to complying with regulatory requirements and minimizing environmental impact. In this research, some successful simple PW treatment technologies have been presented which are not applicable to highly saline water. Therefore, understanding the composition of PW is essential for future plans to reuse it. In the Permian Basin, the high salinity restricts reuse outside the energy sector, rather it is cost-effective to treat PW for hydraulic fracturing. To reuse PW from Permian basin in other purposes like in agriculture sector, farm, industry, there is no alternative to a series of operation although they are highly expensive. Single treatments cannot remove the contaminants to meet any of the reuse standards. Still now, the treatment cost of highly saline PW is higher than the disposal cost, which limits its reuse. Even if the series of operations are more expensive, they can prevent highly contaminated PW from affecting the environment by contaminating it. Thus, if treatment costs can be reduced in the future, the reuse of high-salinity water is likely to become mainstream.

# References

Al-Ghouti, M. A., Al-Kaabi, M. A., Ashfaq, M. Y., & Da'na, D. A. (2019). Produced water characteristics, treatment and reuse: A review. *Journal of Water Process Engineering, 28*, 222-239. https://doi.org/10.1016/j.jwpe.2019.02.001

Alessi, D. S., Zolfaghari, A., Kletke, S., Gehman, J., Allen, D. M., & Goss, G. G. (2017). Comparative analysis of hydraulic fracturing wastewater practices in unconventional shale development: Water sourcing, treatment and disposal practices. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, *42*(2), 105-121. https://doi.org/10.1080/07011784.2016.1238782

Alzahrani, S., Mohammad, A. W., Hilal, N., Abdullah, P., & Jaafar, O. (2013). Comparative study of NF and RO membranes in the treatment of produced water—Part I: Assessing water quality. *Desalination*, *315*, 18-26. https://doi.org/10.1016/j.desal.2012.12.004

Allison, E., & Mandler, B. (2018). Petroleum and the environment. *American Geosciences Institute*, *8*, 1.

Anari, Z., Mohammadi, T., Foudazi, R., & Asghari, M. (2019). Surface modification of PVDF membranes for treating produced waters by direct contact membrane distillation. *Separation and Purification Technology, 224*, 388-396.

Al-Jaser, Z. A., & Hamoda, M. F. (2019). Removal of nickel and vanadium from desalination brines by ion-exchange resins. *Desalination and water treatment*, *157*, 148-156.

Ahmed, M., Kumar, R., Garudachari, B., & Thomas, J. P. (2019). Performance evaluation of a thermoresponsive polyelectrolyte draw solution in a pilot scale forward osmosis seawater desalination system. *Desalination*, *452*, 132-140. https://doi.org/10.1016/j.desal.2018.11.013

Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward. (2022). Texas Produced Water Consortium Report to the Texas Legislature. https://ttu.edu/22-TXPWC-Report-Texas-Legislature.pdf

Chan, L. H., Starinsky, A., & Katz, A. (2002). The behavior of lithium and its isotopes in oilfield brines: Evidence from the Heletz-Kokhav field, Israel. *Geochimica et Cosmochimica Acta*, *66*, 615-623. https://doi.org/10.1016/S0016-7037(01)00800-6

Chang, H., Wang, S., Li, S., & Li, Y. (2019). An integrated coagulation-ultrafiltration-nanofiltration process for internal reuse of shale gas flowback and produced water. *Separation and Purification Technology, 211*, 310-321. https://doi.org/10.1016/j.seppur.2018.09.081

Chen, F., Wang, L., Faramarzi, A., Tayal, A., & Tiwari, D. (2023). Reuse of produced water from the petroleum industry: Case studies from the Intermountain-West Region, USA. *Energy & Fuels, 37*(5), 3672-3684. https://doi.org/10.1021/acs.energyfuels.2c04000

Colorado School of Mines. (2009). *Technical assessment of produced water treatment technologies. An integrated framework for treatment and management of produced water.*

*RPSEA Project 07122-12.*
https://docslib.org/doc/7502519/the-technical-assessment-of- produced-water-treatment

Consulting, A. L. L. (2003). Handbook on coal bed methane produced water: Management and beneficial use alternatives. Prepared for: Groundwater Protection Research Foundation; US Department of Energy, National Petroleum Technology Office, Bureau of Land Management: Washington, DC, USA.

Corrêa, A. X. R., Martins, L. A., Costa, L. L. F., & Leite, A. P. (2010). Use of ozone-photocatalytic oxidation ($O_3$/UV/$TiO_2$) and biological remediation for treatment of produced water from petroleum refineries. *Journal of Environmental Engineering*, *136*(1), 40-45. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000111

Dastgheib, S. A., Nasr, B., Peyravi, M., & Mohammadi, T. (2016). Treatment of produced water from an oilfield and selected coal mines in the Illinois Basin. *International Journal of Greenhouse Gas Control*, *54*, 513-523. https://doi.org/10.1016/j.ijggc.2016.05.002

Drewes, J. E., Horst, J., & McCray, J. (2009). An integrated framework for treatment and management of produced water. RPSEA Project, 07122-12. http://aqwatec.mines.edu/research/projects/Tech_Assessment_PW_Treatment_Tech.pdf

EPA, U.S. Granular Activated Carbon. Available online: https://iaspub.epa.gov/tdb/pages/treatment/treatmentOverview.do?treatmentProcessId=2074826383#content (accessed on 29 January 2019).

Esplugas, S., & Ollis, D. F. (1997). Economic aspects of integrated (chemical+ biological) processes for water treatment. *Journal of Advanced Oxidation Technologies, 2*(1), 197-202. https://doi.org/10.1515/jaots-1997-0103

Eyitayo, S. I., Watson, M. C., & Kolawole, O. (2022). Produced water treatment and utilization: Challenges and future directions. *SPE Western Regional Meeting. SPE.* https://doi.org/10.2118/209310-MS

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L. C., Biak, D. R. A., Madaeni, S. S., & Abidin, Z. Z. (2010). Application of membrane-coupled sequencing batch reactor for oilfield produced water recycle and beneficial re-use. *Bioresource Technology, 101*(18), 6942-6949. https://doi.org/10.1016/j.biortech.2010.04.005

Fan, J., Louie, S. M., & Rodrigues, D. F. (2018). The influence of salinity, pH, temperature and particles on produced water oil quantification precision and accuracy with confocal laser fluorescence microscopy. *Energy & Fuels, 32*(6), 6978-6989. https://doi.org/10.1021/acs.energyfuels.8b01353

Frohlich, C. (2012). Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas. *Proceedings of the National Academy of Sciences, 109*(35), 13934-13938. https://doi.org/10.1073/pnas.1207728109

Garudachari, B., Sahota, S., & Goel, M. (2021). Membrane degasification for desalination industries: A literature review. *Desalination and Water Treatment, 238,* 28-37. doi: 10.5004/dwt.2021.27821

Gil Hurwitz, David J. Pernitsky, Subir Bhattacharjee, and Eric M.V. Hoek *Industrial & Engineering Chemistry Research* **2015** *54* (38), 9431-9439 DOI: 10.1021/acs.iecr.5b02035

Ground Water Protection Council (2023) *Produced water report regulations and practices updates*. GWPC Releases 2023 Produced Water Report | Ground Water Protection Council

Ground Water Protection Council (2019*) Produced Water Report: Regulations, current practices & needs.* Produced Water Report: Regulations, Current Practices & Needs | Ground Water Protection Council (gwpc.org)

Produced water report regulations, current practices and research needs report by Ground Water Protection Council (GWPC). (2019).

Harris, N. B., Frye, K. N., Dubois, M. K., & Hester, T. C. (2009). An integrated geological and petrophysical study of a shale gas play: Woodford Shale, Permian Basin, west Texas.

Hassan, A. A., & Al-Zobai, K. M. (2019). Chemical oxidation for oil separation from oilfield produced water under UV irradiation using titanium dioxide as a nano-photocatalyst by batch and continuous techniques. *International Journal of Chemical Engineering, 2019*(1), 9810728. https://doi.org/10.1155/2019/9810728

Hashemi, F., Rahimi, F., & Madaeni, S. S. (2020). Reclamation of real oil refinery effluent as makeup water in cooling towers using ultrafiltration, ion exchange and multioxidant disinfectant. *Water Resources and Industry*, *23*, 100123. https://doi.org/10.1016/j.wri.2019.100123

Hashemi, F., Rahimi, F., & Madaeni, S. S. (2022). Life cycle and economic assessments of petroleum refineries wastewater recycling using membrane, resin and on-site disinfection (UF-IXMB-MOX) processes. *Process Safety and Environmental Protection*, *162*, 419-425. https://doi.org/10.1016/j.psep.2022.04.027

Hayes, T., Falta, R., & Kurtz, J. (2006). Electrodialysis treatment of coal bed methane produced water: Application issues and projections of costs. *International Petroleum Environmental Conference*, *13*.

Hildenbrand, Z. L., Carlton, D. D., Fontenot, B. E., Meik, J. M., Walton, J. L., Taylor, J. T., ... & Schug, K. A. (2018). Characterizing variable biogeochemical changes during the treatment of produced oilfield waste. *Science of the Total Environment*, *634*, 1519-1529. https://doi.org/10.1016/j.scitotenv.2018.03.388

Hilal, N., Al-Zoubi, H., Darwish, N. A., & Mohamma, A. W. (2015). A combined ion exchange–nanofiltration process for water desalination: I. sulphate–chloride ion-exchange in saline solutions. *Desalination*, *363*, 44-50. https://doi.org/10.1007/s11356-019-05120-2

Igunnu, E. T., & Chen, G. Z. (2014). Produced water treatment technologies. *International Journal of Low-Carbon Technologies*, *9*(3), 157-177. https://doi.org/10.1093/ijlct/cts049

Jebur, M., Alsulaili, A., Al-Johani, H., & Alsahli, A. (2021). Combined electrocoagulation-microfiltration-membrane distillation for treatment of hydraulic fracturing produced water. *Desalination, 500*, 114886. https://doi.org/10.1016/j.desal.2020.114886

Jebur, M., Alsulaili, A., Al-Johani, H., & Alsahli, A. (2023). Integrated electrocoagulation, ultrafiltration, membrane distillation, and crystallization for treating produced water. *Membranes, 13*(6), 597. https://doi.org/10.3390/membranes13060597

Jiang, W., Han, D., Guo, P., & Hou, X. (2022). Characterization of produced water and surrounding surface water in the Permian Basin, the United States. *Journal of Hazardous Materials, 430*, 128409. https://doi.org/10.1016/j.jhazmat.2022.128409

Kaishentayev, D. (2021). Feasibility of low-cost pretreatment methods of produced water in the Permian Basin. (Master's Thesis, Department of Petroleum Engineering, Texas A&M University).

Kassab, M., Abbas, A., Elgamal, I., Shawky, B., Moubark, M., & Hosny, R. (2021). Review on the estimating the effective way for managing the produced water: Case study. *Open Journal of Modern Hydrology, 11*(2), 19-37. https://doi.org/10.4236/ojmh.2021.112002

Khor, C. M., Leong, S. T., & Tan, J. P. (2020). Performance, energy and cost of produced water treatment by chemical and electrochemical coagulation. *Water*, *12*(12), 3426. https://doi.org/10.3390/w12123426

Made-in-China.com. (n.d.). *Manufacturers, suppliers & products in China*. https://made-in-china.com

Malmali, M., Dastgheib, S. A., & Fazel, A. (2017). Selecting membranes for treating hydraulic fracturing produced waters by membrane distillation. *Separation Science and Technology*, *52*(2), 266-275. https://doi.org/10.1080/01496395.2016.1244550

Mohammad-Pajooh, E., Schimmoller, L., & Esmaeeli, M. (2018). On-site treatment of flowback and produced water from shale gas hydraulic fracturing: A review and economic evaluation. *Chemosphere*, *212*, 898-914. https://doi.org/10.1016/j.chemosphere.2018.08.145

Natural Resources Conservation Service (1999) Technical Guide, Section 4: Standard Specifications, United States Department of Agriculture, NRCS, Indianapolis, IN. Indiana | Natural Resources Conservation Service (usda.gov)

New Mexico Produced Water Research Consortium, New Mexico State University (2022). *Produced Water Reuse - Current Drivers and Challenges Technical, Economic, and Health and Safety Issues At the Crossroads.* At the Crossroads: (nmsu.edu)

Reynolds, R. R. (2003). Produced water and associated issues: A manual for the independent operator. Oklahoma Geological Survey Open-file Report, 6, 1-56. SECTION 1 (ou.edu)

Rivas, F. J., Beltrán, F. J., Carvalho, F., & Acedo, B. (2008). Comparison of different advanced oxidation processes (AOPs) in the presence of perovskites. *Journal of Hazardous Materials*, *155*(3), 407-414. https://doi.org/10.1016/j.jhazmat.2007.11.081

Rodriguez, A. Z., Rodriguez, S., Rodriguez, C., Villalobos, D., & Villalobos, J. (2020). Treatment of produced water in the Permian Basin for hydraulic fracturing: Comparison of different coagulation processes and innovative filter media. *Water, 12*(3), 770. https://doi.org/10.3390/w12030770

Sabie, R. P., Pillsbury, L., & Xu, P. (2022). Spatiotemporal analysis of produced water demand for fit-for-purpose reuse—A Permian Basin, New Mexico case study. *Water, 14*(11), 1735. https://doi.org/10.3390/w14111735

Sajtar, E. T. (2008). Toolbox to evaluate treatment technologies for PRB CBM water. (Master's Thesis, Department of Civil and Architectural Engineering, The University of Wyoming)

Sardari, K., Joseph, L., & Han, S. (2018). Electrocoagulation followed by ultrafiltration for treating poultry processing wastewater. *Journal of Environmental Chemical Engineering*, *6*(4), 4937-4944. https://doi.org/10.1016/j.jece.2018.07.022

Sirivedhin, T., McCue, J., & Dallbauman, L. (2004). Reclaiming produced water for beneficial use: Salt removal by electrodialysis. *Journal of Membrane Science*, *243*(1-2), 335-343. https://doi.org/10.1016/j.memsci.2004.06.038.

Smolders, C. A., & Franken, A. C. M. (1989). Terminology for membrane distillation. *Desalination*, *72*(3), 249-262. PII: 0011-9164(89)80010-4 (utwente.nl)

State of New Jersey Department of Health and Safety. *Right to Know Hazardous Substance Fact Sheet. Department of Health | Workplace Health and Safety*. https://nj.gov

Timmes, T. C., Kim, H. C., & Dempsey, B. A. (2010). Electrocoagulation pretreatment of seawater prior to ultrafiltration: Pilot-scale applications for military water purification systems. *Desalination*, *250*(1), 6-13. https://doi.org/10.1016/j.desal.2009.03.021

United States Environmental Protection Agency (USEPA). *About EPA | US EPA*. https://epa.gov

U.S. Energy-Related Carbon Dioxide Emissions. (2023). *Microsoft Word - 2023_emissions_report_4.23.24_Final*. U.S. Energy Information Administration. https://eia.gov

Venzke, C. D., Piccin, J. S., & Dotto, G. L. (2018). Increasing water recovery rate of membrane hybrid process on the petrochemical wastewater treatment. *Process Safety and Environmental Protection*, *117*, 152-158. https://doi.org/10.1016/j.psep.2018.04.023

Virga, E., de Grooth, J., Žvab, K., & de Vos, W. M. (2019). Stable polyelectrolyte multilayer-based hollow fiber nanofiltration membranes for produced water treatment. *ACS Applied Polymer Materials*, *1*(8), 2230-2239. DOI: 10.1021/acsapm.9b00503.

Webb, C., Nagghappan, L. N. S. P., Smart, G., Hoblitzell, J., & Franks, R. (2009, March). Desalination of oilfield-produced water at the San Ardo water reclamation facility, CA. In *SPE Western regional meeting* (pp. SPE-121520). SPE. https://doi.org/10.2118/121520-MS

Wang, L. K., Hung, Y. T., & Shammas, N. K. (Eds.). (2007). Advanced physicochemical treatment technologies (Vol. 5). Totowa, NJ: Humana Press. Advanced Physicochemical Treatment Technologies: Volume 5 | SpringerLink

Whitfield, S. (2017). Permian, Bakken operators face produced water challenges. *Journal of Petroleum Technology*, *69*(06), 48-5. https://doi.org/10.2118/0617-0048-JPT

Zeng, Y., Yang, C., Pu, W., & Zhang, X. (2007). Removal of silica from heavy oil wastewater to be reused in a boiler by combining magnesium and zinc compounds with coagulation. *Desalination*, *216*(1-3), 147-159. https://doi.org/10.1016/j.desal.2007.01.005