TREVI

Cloud Operations & Innovation ("CO+I")

Pre-Market Feasibility Study of the Co-Location of Trevi's Waste (Residual) Heat Driven Forward Osmosis (FO) Desalination Systems with Microsoft Data Centers Sites

CASE 3 (Draft report)

June 16th, 2025

Contents

Background

Trevi's thermally driven Forward Osmosis (FO) technology utilizes low-grade waste heat for desalination and brine concentration to produce clean water. As part of a broader study for the client, Trevi will be evaluating the utilization of waste heat from Data Centers (DC) to determine the effectiveness and impact on the desalination of various water sources with forward osmosis and comparing the Levelized Cost of Water (LCOW) with that of traditional reverse osmosis (RO) or typical incumbent treatment systems required to give comparative performance. The 3 cases are:

- Case 1 – Inland Brackish: FO systems paired with data centers near brackish groundwater sources (<10,000 mg/L TDS), such as in New Mexico or West Texas.

- Case 2 – Coastal Seawater: FO systems treating ocean water (~35,000 mg/L TDS) near coastal data centers with access to fiber and seawater (e.g., San Diego, Corpus Christi).

- Case 3 – Industrial Oil and Gas Produced Wastewater: High-salinity FO deployments (>100,000 mg/L TDS) in oil and gas basins, where data centers can be co-located with upstream or midstream oil and gas drilling operations.

This report will evaluate Case 3 which are industrial oil and gas produced wastewater sites which typically have very challenging wastewater streams with high salinities (high total dissolved solids - TDS) as the source for FO desalination/brine concentration utilizing waste heat from the datacenter. It will explore how location, feedwater salinity, surrounding temperatures and co-location with data centers using 30 °C and 45°C waste heat respectively influences the quantity and quality of desalinated water, as well as the resulting FO LCOW compared to LCOW of the incumbent wastewater treatment system typically required to treat the wastewater to the same level as that of FO. High-level engineering schematics, including mass balances and plant footprint estimates, are provided.

The impact of transforming an otherwise wasted resource (low-grade heat) into a valuable one (clean usable water) for all the above 3 cases with varying conditions like electricity costs etc, will be evaluated in the fourth phase of this study – Case 4.

Trevi Systems has identified 3 U.S. cities - Dallas–Fort Worth, Houston and Denver as major cities which have significant oil & gas drilling activities, have suitable infrastructure for data center growth and have water needs. In addition, 3 cities in 3 Middle Eastern countries have also been identified as having the similar criteria of oil and gas drilling activities, have suitable infrastructure for data center growth and have water needs. These cities are Riyadh in Saudi Arabia, Abu Dhabi in the United Arab Emirates (UAE) and Muscat in Oman. A more detailed explanation on the rationale for the selection of these cities will be highlighted later in this report.

Why Oil & Gas Produced Wastewaters are Challenging

Treating these produced oil and gas wastewaters is challenging due to the high salinity levels of these types of waters Typical U.S. produced water ranges from 0.5% to >40% salinity, though most sits between 10–30% (TDS 100,000–200,000 mg/L). In the Permian Basin, expect 20–150 g/L (20,000–150,000 mg/L), with average around 90,000 mg/L, and spot samples reaching 200,000 mg/L. These salinity levels are 3–15 times the saltiness of seawater, underscoring why treatment and disposal are costly and complex.

Produced water is essentially formation water — ancient, trapped fluids in the pores of sedimentary rocks. Over millions of years, as basins filled with sediments and were buried deeper due to the evaporation of ancient seawater concentrated salts before burial, water-rock interactions (like ion exchange, mineral dissolution/precipitation) further modified salinity and ionic composition and the thermal maturation of organic matter and compaction squeezed water from clay minerals and other formations. Because these waters have been isolated from meteoric (fresh) water recharge for millions of years, their salinities are extremely high — often 100,000–200,000 mg/L TDS.

The variability in the salinity of the produced water can range from 20,000 to over 200,000 mg/L even within the same basin and designing a wastewater treatment system will need as accurate data sampling of input feedwaters as possible. Causes for wide swings in variability include geologic heterogeneity where different rock types and depositional environments have different porosity, permeability, and mineralogy, influencing how water is retained and altered; stratigraphic depth where shallower formations may still be connected to meteoric recharge or diluted by younger waters, while deeper zones are isolated and highly saline; the mixing of formation waters where fluids from different depths and geologic units can mix during hydraulic fracturing and production, leading to variable salinity signatures even from the same well pad and localized dissolution of evaporites where formations containing halite or anhydrite beds can dramatically spike salinities when dissolved by formation water.

As an example, the Permian Basin in the US has 2 smaller basins. The Delaware Basin typically has formation waters ranging 50,000–125,000 mg/L TDS, but the deeper Wolfcamp waters may exceed 200,000 mg/L. The Midland Basin shows even higher values in places, with produced water salinities recorded up to >150,000 mg/L.

Blondes, M.S. et al. (2019). U.S. Geological Survey National Produced Waters Geochemical Database v2.3 (PROVISIONAL). USGS. https://energy.usgs.gov

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Kharaka, Y.K., Hanor, J.S. (2003). Deep fluids in the continents: I. Sedimentary Basins. In Treatise on Geochemistry.

Nicot, J.P. et al. (2017). Brine extraction and injection effects on basin-scale hydrogeology and produced water management. Environmental Science & Technology.

Why Do Brackish Groundwater, Seawater, and Produced Water Have Different Salinities?

Since our extended investigation project has covered brackish groundwater, seawater and produced oil and gas wastewater as a source for desalination, the above question on the huge variation in salinities arises. The short answer is that it comes down to their origins, history of interaction with rocks and minerals, isolation time, and hydrologic setting.

I. Source and Age of Water

a. Freshwater / Brackish groundwater

Recent water from rain, rivers, or shallow aquifers. Limited time for rock interaction or evaporation to concentrate salts. Brackish water typically results from mixing of freshwater with saline waters (like seawater intrusion, or upward leakage from saline formations).

b. Seawater

Originates from ancient and modern oceans, with salinity stabilized at ~35,000 mg/L over geologic time by a balance between evaporation, precipitation, river runoff, and hydrothermal circulation at mid-ocean ridges.

c. Produced water

Trapped in the pores of sedimentary rocks for millions to hundreds of millions of years. Underwent intense evaporation (in ancient basins), mineral dissolution (e.g., halite, anhydrite), and water-rock geochemical reactions. Isolated from fresh water recharge.Salinities can reach up to 15× seawater in closed, deep, thermally mature formations.

II. Geochemical Processes

a. Brackish groundwater: Limited ion exchange and rock-water interaction. Tends to pick up some Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-} from local minerals.
b. Seawater: A well-mixed global reservoir, with major ions (Na^{+}, Cl^{-}, Mg^{2+}, SO_4^{2-}, Ca^{2+}, K^{+}) in stable ratios. Salinity set by long-term balance of river input and oceanic processes.
c. Produced water: Prolonged water-rock interaction dramatically alters chemistry by dissolution of evaporite minerals (halite, anhydrite), ion exchange (Na^{+} replacing Ca^{2+} or Mg^{2+}) and thermal maturation liberating ions from clays and organics

III. Isolation Time

a. Brackish groundwater: Often connected to surface recharge; can be seasonally or annually renewed.
b. Seawater: Continuously mixed and exchanged globally over decades to millennia.
c. Produced water: Geologically isolated for millions of years. No freshwater influx, so evaporation and geochemical processes dominate, concentrating salinity over time.

In a nutshell, brackish groundwater is mildly saline because of limited exposure to rocks and salt sources. Seawater is moderately saline and globally mixed, balancing inputs and evaporation. Produced water is highly saline because it's ancient, deeply buried, isolated, and has spent millions of years interacting with salty rocks and evaporites.

In the next section, we will discuss why reverse osmosis (RO) struggles as salinity increases, why energy consumption increases correspondingly and why evaporators like mechanical vapor recompression (MVR) take over at high TDS like 200,000 mg/L.

Why Energy Consumption Demands Increase as Brine Concentration TDS Increases

The main reason why RO energy costs and CAPEX increase with increasing salinity is due to the increasing osmotic pressure. The osmotic pressure (π) for a salt solution rises linearly with salt concentration. To desalinate via RO (and even FO), the applied pressure must exceed the osmotic pressure of the feedwater.

Osmotic pressure equation (approximate for dilute solutions) is directly correlated to molar concentration and temperature. At higher salinity, osmotic pressure rises steeply:

- Seawater (~35,000 mg/L TDS): $\pi \approx 27–28$ bar
- Produced water (~100,000 mg/L TDS): $\pi \approx 80$ bar
- 200,000 mg/L TDS: $\pi \approx 160$ bar

Most commercial RO membranes operate at max ~83 bar (1,200 psi). Above this, you need specialized membranes and high-pressure equipment — which:

- Increases CAPEX (thicker pressure vessels, specialized membranes)
- Increases energy costs because more pumping power is required to overcome osmotic pressure and still get a permeate flow.

In addition, at higher salinities, there is lower water recovery meaning one recovers less fresh water per unit of feed because concentrating the brine raises its osmotic pressure and there are also increased scaling and fouling risks increase (e.g., $CaSO_4$, silica, halite precipitation). Typical recoveries are:

- Seawater RO: 40–50% recovery
- Brackish RO: 75–85% recovery
- High-salinity RO (>50,000 mg/L): 10–30% or lower

This means more brine disposal and larger systems to process the same freshwater volume — inflating both CAPEX and OPEX.

Lastly, RO membranes degrade in performance at very high TDS:

- Flux declines (due to high osmotic pressure)
- Scaling and fouling rates increase
- Membrane lifespan shortens under high-pressure, high-TDS conditions

Ultra-high pressure reverse osmosis (UHPRO) which is a relatively newer type of RO can go up to around 120 bar but the CAPEX and energy costs do increase fairly significantly as RO power requirements rise nonlinearly with salinity. In addition, UHPRO's technology is not as well standardized and commoditized as standard RO up to 80 bar.

Typically evaporators take over brine treatment beyond 100,000 mg/L as RO is no longer economical or technically viable. Evaporators don't rely on osmotic pressure — they separate water by phase change (boiling/condensation), not membrane filtration. Evaporators are capable of handling saturated brines — MVR systems can concentrate produced waters to near-zero liquid discharge (ZLD) levels. Evaporators also have stable water recovery rates (~90–95%) even at extremely high TDS and are insensitive to feedwater osmotic pressure — higher TDS mainly affects scaling risk and heat transfer efficiency, not system pressure. However, the downsides are evaporators are extremely energy-intensive (electricity or steam input) and have relatively high CAPEX due to all the stainless steel and special materials used to tolerate the high heat.

A quick recap of how Trevi's FO technology is able to overcome this osmotic pressure of high salinity solutions is because Trevi's FO utilizes a very concentrated draw solution on one side of the membrane (to exert an osmotic pressure to pull water from the saline solution) and is not relying on exerting an external pressure to overcome the osmotic pressure of the saline solution. As a result, Trevi's FO becomes more competitive when it is utilized for saline feed water sources (like produced oil and gas wastewaters) which are beyond the limits of standard RO as we will demonstrate later in this study and technically is competing against UHPRO and evaporators.

Waste Heat Utilization Scenario & Heat Pump Assumptions

As in Case 1&2, this analysis considers a nominal 1 MW thermal cooling load from a data center, with waste heat rejected at either 30 °C or 45 °C and a return temperature fixed at 18 °C and 30 °C respectively in a closed-loop cooling configuration, as shown in Figure 1. In comparison to Case 1 and Case 2, Trevi's FO system here will operate at 90 °C rather than at 85 °C, requiring a temperature lift of up to 60 °C (from 30 °C), and 45 °C lift in the 45 °C case. This higher lift is needed due to the high salinity of the source water which increases the osmotic pressure that Trevi's FO draw solution has to overcome.

In any event, both are considered high-lift applications and require appropriately designed heat pumps. A detailed evaluation of heat pumps was conducted and our calculations for the nominal case of 30C heat, 18C return for a rotational heat pump with a supplier measured Coefficient of Performance (COP) of 3.3 at these conditions and a COP of 3.3 is used as the basis for Trevi's FO system's performance evaluation.

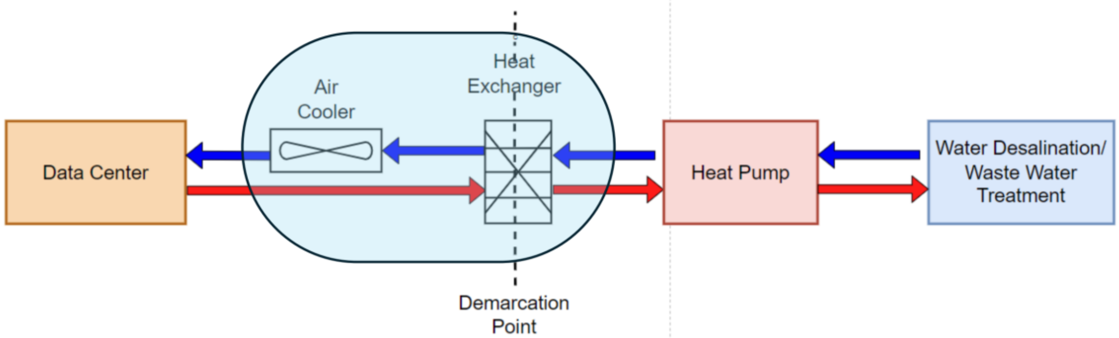


Fig. 1 Trevi's FO System Integrated into the DC cooling system with Heat Pump

Calculations of Coefficient of Performance (COP) for Heat Pumps as a Function of Surrounding Temperature & Assumptions

In Case 1 (inland brackish ground water source), we compared running our FO plant using waste heat from the datacenter against running it against ambient air to see the benefits of the constant datacenter heat source. For Case 2 (seawater source), we ran the FO plant using the seawater as source heat to assess the benefits of using datacenter heat instead of seawater as heat source. In Case 3, we will be assessing our FO plant similarly to that of Case 1, using waste heat from the datacenter against running it with ambient air cooling to see the benefits of the constant datacenter heat source. Typical oil and gas sites are inland and have very limited access to water sources which makes treatment of the produced wastewater for reuse extremely attractive.

As part of the calculations for the LCOW for FO without waste heat, the formula is as such:

=Annualized (Electricity Cost + Thermal costs (with HP & ambient air cooling & no WH)+ FO CAPEX+FO OPEX+ Heat Pump CAPEX)/1000

COP for ambient air is required to calculate the Thermal costs (with a HP utilizing air cooling and no WH) by using the average monthly ambient air temperatures of each city. The monthly average ambient temperatures for each city are referenced and the COP calculation results are shown in Appendix 1.

It is important to note that the COP for the HP for the DC which gives out waste heat at 30 deg C = 3.3 and was used to calculate the LCOW for FO with waste heat at 30 deg C, the corresponding formula:

=Annualized (Electricity Cost + Thermal costs (with HP & WH @ 30 deg C)+ FO CAPEX+FO OPEX+ Heat Pump CAPEX)/1000

For the COP for the HP for the DC which gives out waste heat at 45 deg C, we adjusted the COP using the ideal carnot efficiency for 30C and the ideal carnot efficiency for 45C and then increased the actual manufacturers carnot efficiency at the first case, yielding a COP of 4.4.

This COP was used to calculate the LCOW for FO with waste heat at 45 deg C, the corresponding formula :

=Annualized (Electricity Cost + Thermal costs (with HP & WH @ 45 deg C)+ FO CAPEX+FO OPEX+ Heat Pump CAPEX)/1000

Case 3: Oil & Gas Produced Wastewater Datacenter Site Selection

The following six cities—Dallas-Fort Worth, Houston, Denver, Riyadh, and Abu Dhabi—were selected for the Case 3 evaluations. These cities were chosen not only because of their substantial oil and gas operations and reserves, but also due to their high volumes of produced water and relatively high levels of water stress. Additionally, these cities have burgeoning local technology ecosystems, positioning them well to meet the increasing demand for international connectivity and digital infrastructure. Further information on why each of these cities were selected will be highlighted in the latter section of this report.

Dallas-Fort Worth

Dallas-Fort Worth has proximity to the Barnett Shale and Permian Basin and has significant oil & gas operations in the region. Produced wastewater volumes are high due to nearby Permian Basin activities. The Permian Basin accounts for a substantial portion of U.S. oil production, leading to significant produced water volumes. There is also water stress when combining scarcity, population demand, and pricing outlook — driven by drought, oil & gas water use, and explosive metro growth.

Houston

Houston is known as the energy capital of the U.S. and has extensive oil & gas infrastructure and operations. It also faces substantial water pricing pressure from infrastructure upgrades, alongside high growth and moderate scarcity.

Denver

Denver has proximity to the Denver-Julesburg (DJ) Basin, a significant oil & gas producing region. Moderate volumes of produced water are associated with DJ Basin activities. It was reported that water usage for hydraulic fracturing has more than doubled from 2013 to 2022, with average volumes increasing fourfold. Denver is also highly vulnerable to long-term scarcity due to its dependence on the overdrawn Colorado River

Riyadh, Saudi Arabia

Riyadh in Saudi Arabia is a significant oil producing country with significant reliance on desalination. Their oil extraction methods like steam injection and fracking are water-intensive. Rapid expansion for their data center initiatives under Vision 2030 with key players include STC, Mobily, Oracle, and Google Cloud (developing in Dammam).

Abu Dhabi, UAE

Abu Dhabi in the United Arab Emirates is major oil producing country and there is also high water scarcity with a heavy reliance on desalination. Data center presence and growth is also increasing with major players include Khazna, Equinix, Microsoft Azure, Oracle, and AWS.

Muscat, Oman

Muscat in Oman is another oil producing country in the Middle East with high water scarcity and minimal freshwater resources. Oman is in the early-stage development to becoming a strategic cable hub with a strategic location for cable landings.

Case 3: Produced Oil & Gas Desal/WWTP Datacenter Assumptions

For our Case 3, Trevi will assume an incoming salinity of 100,000 mg/L total dissolved solids (TDS) and a final brine concentration of 200,000 mg/L which is typically the brine concentration before crystallizers are used to create solids for disposal enabling zero liquid discharge (ZLD). In the produced oil and gas wastewater treatment operations, minimum liquid discharge (MLD) is typically the goal for more oil and gas producers as it is cheaper to dispose of less brine via deep well injection or evaporation ponds or trucking as it is to have an onsite immobile CAPEX and OPEX intensive crystallizer for ZLD. The solids from ZLD will also need to be disposed off in landfills or trucks.

1MW of cooling based on the energy requirement for Trevi's thermal FO desalination plant is projected to produce 700m^3/day of desalted water for 100,000 mg/L of TDS. This desalination capacity is less than that for Case 1 and Case 2 which were brackish ground water and seawater sources respectively due to the high starting concentration (high TDS) of the incoming feed waters. At higher feed concentrations, more energy is required to desalinate/concentrate the brine and so the overall output capacity of the FO plant for Case 3 is less.

Trevi's FO system can use its standard draw solution which is capable of achieving the osmotic pressure sufficient to achieve the required brine concentration for these produced waste waters. However, the thermal and electrical power required for this FO plant vs that for Case 1 and Case 2 is more due to incoming feed and brine output TDS from the FO plant. See below for comparisons.

FO Electrical (Brackish & Seawater)	1.3	kWh/m3
FO Electrical (Produced)	4.5	kWh/m3
FO Thermal (Brackish & Seawater)	35	kWh/m3
FO Thermal (Produced)	50	kWh/m3

The Plant is designed to produce potable water but is not allowed to used as potable water in the US due to regulatory restrictions. It is usually advised that the cleaned water should be used for non-edible agriculture, or industrial applications like cooling, cleaning and should not be used for potable water purposes. Produced wastewater has an extremely high amount of unknown chemicals which the oil and gas companies inject into the ground in order to extract oil. Amongst these are also many carcinogenic compounds and while we know the water treatment processes can remove these compounds, the liability for utilizing this water for drinking water or edible purposes is too large. More information will be shared in a later section. Permeate TDS will be less than 300mg/l as shown in Table 1.

DC Site location Criteria

The DC, heat pump, FO plant and the produced water source should all be co-located together not more than 500-1000 yards apart.

Data centers supplying waste heat to a FO brine concentration plant must be located near the oil and gas operations for easy access to the produced oil and gas wastewaters for efficient cooling, but equally critical is the co-location of a forward osmosis (FO) seawater desalination plant and the heat pump directly adjacent to or within the data center campus.

This close physical integration is essential because the FO desalination plant and heat pump utilizes low grade waste heat (in the form of 30 deg C or 45 deg C water) supplied by the DC to the forward osmosis brine concentration plant to drive draw solution regeneration for the production of clean water which could be used for different applications. The forward osmosis brine concentration plant could also be used to supply the DC facility with a sustainable, reliable source of clean water needed for cooling and operations.

Co-locating the DC, heat pump, FO plant and the produced water source minimizes water transport energy, reduces infrastructure complexity, and enables a closed-loop system where produced is efficiently converted into high-quality process water on-site. This proximity ensures optimized operational efficiency and supports the data center's long-term sustainability in water-constrained inland regions.

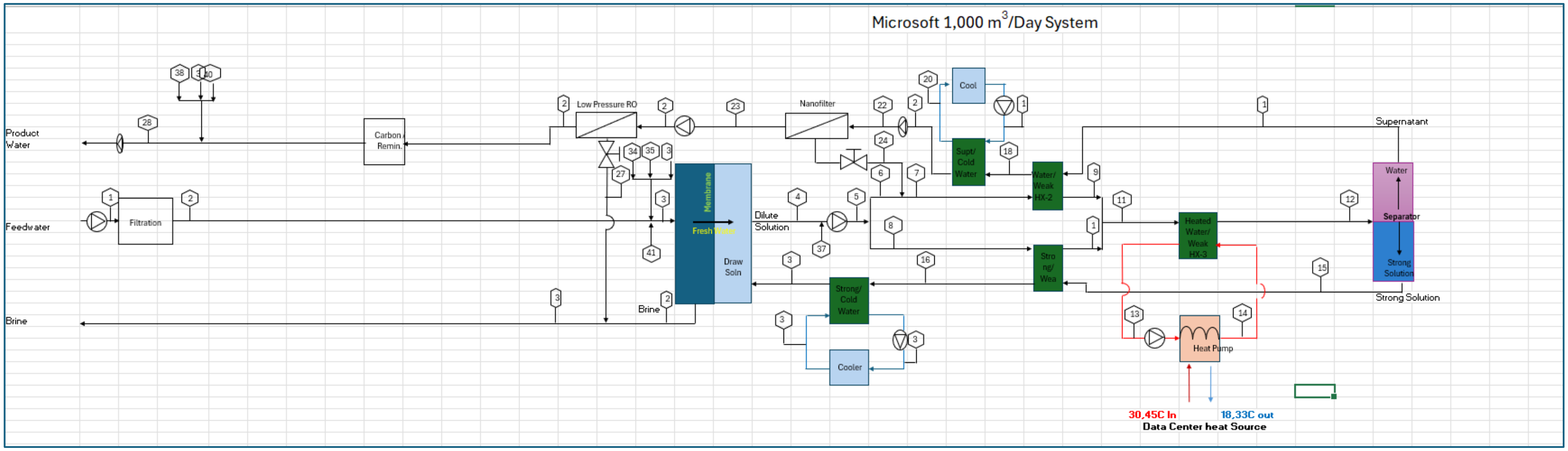
Designing the FO Plant

Based on the parameters and assumptions described in this report for Case 3, and using Trevi's 8 FO systems built to date (including one for oil and gas produced wastewaters), a 700 m3/day FO produced water desalination plant was designed with a CAPEX of $2,557,664 and annual OPEX of $256,476 for chemicals and consumables (excluding energy which is calculated separately). This is an increase in the CAPEX and annual OPEX for Case 1 and 2 which were for brackish groundwater and seawater desalinations mainly because of the extensive pre-treatment and post treatment requirements for produced oil and gas wastewaters and their high salinities making it an extremely challenging type of water to treat.

Brackish water and seawater are many magnitudes "cleaner" and less challenging to treat than produced oil and gas wastewaters. A detailed PFD with mass balances was also developed. Please see the next page for a brief overview of it. A more detailed diagram can be found in the corresponding EXCEL sheet along with mass balances sent separately.

PFD & Mass Balance

PFD for 701 m3/day Produced Wastewater O&G FO Desalination plant



Mass Balances for 701 m3/day Produced Wastewater O&G FO Desalination plant

System Conditions — Design Conditions

Stream Description	Feedwater	Filtered Feed	Feed Water to FO Membranes	Diluted Draw Solution	Diluted Draw to HXs	Diluted Draw to Water / Weak HX-2	Diluted Draw and Nano Reject to HX-2	Diluted Draw to Strong / Weak HX-1	Warm Dilute Draw from HX-2	Warm Dilute Draw from HX-1	Warm Dilute Draw to Boost HX-3
Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Temperature (deg C)	6 - 33	6 - 33	6 - 33	30.2	30.2	30.2	30.2	30.2	80.1	76.1	76.5
Flowrate (m^3/h)	83.3	83.3	83.3	516.0	516.0	56.5	58.8	459.6	58.8	459.6	518.4
Mass Flowrate (kg/hr	89575	89575	89575	560459	560459	61326	63805	499133	63805	499133	562938
Pressure (psi)	30	27	27	5	23	23	23	23	19	19	19
Pressure (bar)	2.07	1.86	1.86	0.34	1.59	1.59	1.59	1.59	1.31	1.31	1.31
TDS (mg/l)	100000	100000	100000	0	0	0	0	0	0	0	0
Polymer Concentration (wt%)	0%	0%	0%	73.2%	73.20%	73.20%	71.11%	73.20%	71.11%	73.20%	72.96%
pH	7.8	7.8	6.5	6.5	7	7	7	7	7	7	7
Heat Transfer (kW)			kWh/m^3						2265	16202	
Supplied Heat	3155	kW	75.7								
Supplied Cooling	2259	kW	54.2								
Density									1026	1026	1026
m3/day per m3									2.32	1.18	1.14
l/min									80.6	41.0	39.6

Stream Description	Hot Dilute Draw	Hot Water Return from Boost HX-3	Hot Water Feed to Boost HX-3	Hot Conc. Draw	Cooled Conc Draw	Super-natant	Cooled Super-natant	Cooling Water to HX-4	Return Cooling Water from HX-4	Chilled Super-natant	Pressurized Super-natant to Nanofilter
Parameter	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Temperature (deg C)	85.0	82.0	90.0	85.0	35.0	85.0	42.0	25.0	32.0	30.0	30.0
Flowrate (m^3/h)	518.4	349.1	349.1	472.2	472.2	46.2	46.2	78.9	78.9	46.2	46.2
Mass Flowrate (kg/hr	562938	337744	337744	512131	512131	45286	45286	78631	78631	45286	45286
Pressure (psi)	15	3	5	15	10	15	13	5	3	11	110
Pressure (bar)	1.03	0.21	0.34	1.03	0.69	1.03	0.90	0.34	0.21	0.76	7.58
TDS (mg/l)	0	0	0	0	0	0	0	0	0	0	0
Polymer Concentration (wt%)	72.96%	0.00%	0.00%	80.00%	80.00%	1.00%	1.00%	0.00%	0.00%	1.00%	1.00%
pH	7	7	7	7	7	7	7	7	7	7	7
Heat Transfer (kW)	3155		-3155		-16202		-2265		639	-639	
Density	1024	1025	1025	1078.05	1076.13	1076.13	1076.13	1076.13	1076.13	1076.13	1076.13
m3/day per m3	1.18	1.14	2.32	3.73	3.9	1.84	2.06	1.84	2.06	3.9	3.9
l/min	41.0	39.6	80.6	129.5	135.4	63.9	71.5	63.9	71.5	135.4	135.4

Stream Description	Nanofilter Permeate	Nanofilter Reject	Pressurized RO Feed	Low Pressure RO Permeate	Low Pressure RO Reject	Remineralized Product Water	FO Membrane Brine	System Brine	Chilled Strong Draw	Return Cooling Water from HX-5	Cooling Water to HX-5
Parameter	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
Temperature (deg C)	30.0	30.0	30.0	30.0	30.0	30.0	35.8	35.4	30.0	32.0	25.0
Flowrate (m^3/h)	43.9	2.308	43.9	41.7	2.2	41.7	39.5	41.7	472.2	209.50	209.50
Mass Flowrate (kg/hr	43585	1701	43585	41488	2098	41488	#VALUE!	47779	512131	224533	224533
Pressure (psi)	5	23	105	10	10	5	10	10	6	3	5
Pressure (bar)	0.34	1.59	7.24	0.69	0.69	0.34	0.69	0.69	0.41	0.21	0.34
TDS (mg/l)	0	0	0	0	0	0	211111	200000	0	0	0
Polymer Concentration (wt%)	0.00%	20.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	80.00%	0.00%	0.00%
pH	7	7	7	7	7	7	7	7	7	7	7
Heat Transfer (kW)									-1620		1620
Density	1083.27	1083.27	972	990.2	993.4	993.4	993.4	1020	1025.1	968	968.8
m3/day per m3	2.73	2.73	1.18	1.18	1.18	1	0.18	1.32	1.32	17.9	17.9
l/min	94.8	94.8	41.0	41.0	41.0	34.7	6.2	45.8	45.8	621.5	621.5

Stream Description		Chemical Injections	Sulfuric Acid (35%)	Sodium Hypo Chlorite to Feed Water (5%)	Sodium Meta Bisulfite (10%)	Sodium Hydroxide to Weak Draw (5%)	Sodium Hydroxide to Product Water (5%)	Calcium Chloride	Sodium Hypo Chlorite to Product Water (12%)	Scale Inhibitor
Parameter			**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**
Temperature (deg C)			25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Flowrate (m^3/h)		ml/min	166.930	69.2	785.2	308.8	54.2	48.4	10.4	9.6
Mass Flowrate (kg/hr		g/min	198.4	69.4	810.2	316.7	55.6	104.0	10.4	11.6
Pressure (psi)			27	27	27	5	5	5	5	27
Pressure (bar)			1.86	1.86	1.86	0.34	0.34	0.34	0.34	1.86
TDS (mg/l)			0	0	0	0	0	0	0	0

Levelized Cost of Water (LCOW) Analysis for FO and UHPRO + Evaporator Scenarios

This section presents the Levelized Cost of Water (LCOW) assumptions for four distinct system configurations, including FO with and without data center (DC) waste heat integration, and a comparative UHPRO + Evaporator scenario assuming similar input and output plant performance. All systems are modeled to deliver 701 m^3/day of treated water which is what 1 MW of waste heat can achieve with a FO desalination system for oil and gas produced wastewaters.

Scenarios Evaluated:

1) FO Only –Air Cooled with Heat Pump:

A 701 m^3/day Forward Osmosis (FO) plant operating independently inland, without access to data center waste heat. The system uses air cooling and a heat pump to manage thermal and cooling requirements.

2) FO + DC Waste Heat (30°C Inlet & 18°C Outlet):

An FO plant utilizing 30°C waste heat water from a data center, feeding Trevi's heat pump, and producing 18°C outlet water with the heat pump. The cooled water will be recirculated to the data center for reuse in cooling using a heat exchanger as shown in Fig 1 above.

3) FO + DC Waste Heat (45°C Inlet & 33°C Outlet):

Similar to Scenario 2, but with higher-quality waste heat at 45°C. Trevi's heat pump would cool the stream to 33°C as before.

4) Benchmark UHPRO + Evaporator System:

A 701 m^3/day Ultra High Pressure Reverse Osmosis (UHPRO) + Evaporator plant powered entirely by electricity, designed to achieve the same water treatment performance as the FO systems for comparison purposes.

Table 1 summarizes the key techno-economic input variables used in the LCOW analysis for each scenario.

Temperature lift of DC heat with FO **Note: Lift is the average temperature from the cold side to the hot side. Thus for 30C, the average cold side = 24C and for 45C, the average cold side = 39. The lift on the hot side is an average of 85 (=(90C + 80C)/2) & therefore the difference is 85-24 = 61 or 85-39 = 46*	46-61°C

COP for Air Cooling for FO plant (No waste heat from DCs for FO plant)	Dependent on monthly ambient surrounding seawater temperature – See Appendix 1
COP for Air Cooling for FO Plant (45% of Carnot & with waste heat from DCs for FO plant with 30 deg C in & 18 deg C out)	3.3
COP for Water Cooling for FO Plant (45% of Carnot & with waste heat from DCs for FO plant with 45 deg C in & 33 deg C out)	4.4
Electricity Cost	0.08c/kWh
Heat Pump CAPEX	$500,000
Wastewater feed salinity	100,000mg/l
Brine discharge	200,000mg/l
System recovery rate (FO and RO)	50 %
FO thermal Energy	50 kWh/m^3
FO Electrical Energy	4.5 kWh/m^3
UHPRO & MVR Electrical Energy	28.7 kWh/m^3
FO or RO system Availability	98%
FO or RO Permeate Water Quality	<300mg/l

Table 1 TEA Input variables

Other assumptions and scenarios include:

1) The DCs supplies waste heat to the Trevi supplied heat pump which lifts it to the required 90°C for the FO plant draw solution separation/regeneration.
2) Six produced oil and gas city locations in the US and Middle East are evaluated. These sites are:
    a. Dallas Fort Worth, Texas
    b. Houston, Texas
    c. Denver, Colorado Texas
    d. Riyadh, Saudi Arabia
    e. Abu Dhabi, United Arab Emirates
    f. Muscat, Oman

   The average air monthly temperatures of these cities (Appendix 1) will be evaluated to see if they have an impact on the economics for the LCOW of FO as a standalone plant and compared with the LCOW of FO utilizing the waste heat from data centers
3) The CAPEX for the comparative system to that of the FO used is that of an ultra-high pressure RO system + an evaporator to achieve the same salinity (200,000 mg/L TDS brine) which FO can achieve at this site while still allowing for deep well injection or other disposal methods.

Results Summary:

Using Table 1 above, the various scenarios are calculated below for the 6 different geographical locations and the results shown in Table 2 below. Since these treatment costs are for oil and gas produced water sites, a treatment cost (LCOW) per barrel which is normal nomenclature in the oil and gas industry is also depicted right below. A demonstration of how the numbers for Dallas Fort Worth was derived is shown in Appendix 2.

Levelized Cost of Water - LCOW ($/m3)	LCOW FO (No WH)	LCOW (with DC WH)	LCOW (with DC WH)	LCOW UHPRO + MVR
Location / Temperature	Ambient Temp	30C In + 18C Out	45C In + 33C Out	Ambient Temp
Dallas	$3.68	$3.60	$3.29	$4.50
Houston	$3.64	$3.60	$3.29	$4.50
Denver	$3.84	$3.60	$3.29	$4.50
Midland, Tx	$3.71	$3.60	$3.29	$4.50
Oaklahoma City	$3.75	$3.60	$3.29	$4.50
Abu Dhabi	$3.48	$3.60	$3.29	$4.50
Riyadh	$3.57	$3.60	$3.29	$4.50
Muscat	$3.48	$3.60	$3.29	$4.50

Cost of Treatment per Barrel ($/bbl)	LCOW FO (No WH)	LCOW (with DC WH)	LCOW (with DC WH)	LCOW UHPRO + MVR
Location / Temperature	Ambient Temp	30C In + 18C Out	45C In + 33C Out	Ambient Temp
Dallas	$0.59	$0.58	$0.53	$0.73
Houston	$0.59	$0.58	$0.53	$0.73
Denver	$0.62	$0.58	$0.53	$0.73
Midland, Tx	$0.60	$0.58	$0.53	$0.73
Oaklahoma City	$0.60	$0.58	$0.53	$0.73
Abu Dhabi	$0.56	$0.58	$0.53	$0.73
Riyadh	$0.58	$0.58	$0.53	$0.73
Muscat	$0.56	$0.58	$0.53	$0.73

Table 2. TEA Analysis for Produced Oil & Gas Wastewater Desalination/Brine Concentration

What is immediately evident is forward osmosis as a technology with or without waste heat from a data center is the more cost-effective technology for the treatment of challenging, high salinity produced oil and gas wastewaters compared ultra-high pressure reverse osmosis coupled with an evaporator which the incumbent technology of choice required to meet the same performance as forward osmosis.

Trevi's high osmotic pressure of our proprietary draw solution makes our FO technology more suitable and an elegant solution for brine concentration of high salinity brines as opposed to reverse osmosis which is limited by the physical attributes of a RO system and evaporators which are highly energy intensive and CAPEX heavy. Comparing this with Case 1 for brackish inland desalination where the brine was concentrated up to 150,000 mg/L, Trevi's FO was competitive and cheaper than ultra-high pressure reverse osmosis which was needed to get up to such high brine concentrations. In contrast for Case 2 which was for seawater desalination and the brine concentration was up to 100,000 mg/L, Trevi's FO was not as competitive as seawater RO if not taking into account other factors like cooling and carbon credits.

When looking at the cost estimates of brine concentration for the 6 cities for data center supplied 30 deg heat source or the 45 deg heat source, they are the same unit economics across all the cities. This is because of the consistent heat source from the data centers together with the heat pumps enables consistent delivery of energy. In addition, it is important to note that the LCOW does not include local construction of the plant, delivery / shipping costs, permitting etc and other miscellaneous costs which are location specific and can only be flushed out with a more detailed site specific project cost estimate which would then probably results in some slight differences in total cost of treatment for each site.

Reviewing the cost estimates amongst the three FO scenarios, it is clear that a better heat source at 45 deg C from a data center consistently enables better numbers than with a 30 deg heat source and just using ambient air for cooling for a FO system without a data center heat source. This is due to the higher heat lift requirements for the FO plant which treating more concentrated and saline brine. It would be interesting to see how a slightly higher heat source say of 65 deg C heat source from a data center could improve the treatment costs.

Comparing the 30 deg heat source data center LCOWs to that of the LCOW using just ambient air for FO cooling, utilizing 30 deg heat from the data centers yields a slightly lower cost of treatment for all the US cities but not for the Middle Eastern cities. This is because Middle Eastern cities have typically higher year-round temperatures and the ambient surrounding air temperatures are higher than 30 deg C and can provide better direct heating than the 30 deg heat source from a data center.

Hence a higher consistent heat source of 45 deg C or higher from a data center or having a FO plant co-located with a data center in a location/site which has consistent lower surrounding ambient temperatures enables more attractive desalination/brine concentration cost numbers for Case 3. If taking into account, cooling credits or carbon credits, the FO desalination will vastly increase in attractiveness in comparison to the incumbent UHPRO + evaporator treatment alternatives.

It would be interesting to explore Canada and Norway for Case 4 as these countries have significant oil producing activities overlapping with a growing need for more data center infrastructure. Regardless, this pairing of FO desalination/brine concentration plant for oil and gas produced wastewaters with data center waste heat fosters a resilient, cost-efficient link between energy and digital infrastructure.

Footprint and Uses

A 701 m3/day produced oil and gas FO desalination/brine concentration system's footprint is approximately 14.2% larger than a 1000 m3/day equivalent size Seawater RO system's footprint due to extensive pre-treatment requirements, compared with Case2. Additional pre-treatment equipment will be needed to remove excess oil and in addition, the membranes will also yield lower fluxes due to the high brine concentration they are treating and possibly more membranes will be required.

Datacenter Size – Thermal load	FO Plant Size (m^3/day)	FO Plant area - sq ft and (sq m)
1MW	701	1750 (2000)

Potential Applications for FO Treated Produced Oil & Gas Wastewaters

The Toxicity of Produced Oil & Gas Wastewaters

Produced water, the largest byproduct of oil and gas extraction, poses significant environmental and public health risks due to its complex and often hazardous composition. One of its primary dangers is its extremely high salinity, which frequently exceeds 100,000 mg/L — nearly three times that of seawater. When spilled or improperly managed, this hypersaline water can severely damage freshwater ecosystems, degrade soil quality, and impair agricultural and drinking water resources. Beyond salinity, produced water contains a wide range of dissolved toxic chemicals, both naturally occurring from geological formations and anthropogenic, introduced through drilling, hydraulic fracturing, and well maintenance processes.

This wastewater stream is further complicated by the presence of oil, grease, and organic compounds, including toxic hydrocarbons, aromatics like benzene and toluene, and volatile organic compounds that can contaminate air and water. A particularly concerning component is naturally occurring radioactive materials (NORM) such as radium-226, radium-228, and lead-210, which are mobilized from subsurface formations during production and can accumulate in scales and sludges. Produced water also frequently carries heavy metals like arsenic, mercury, lead, and cadmium, posing long-term risks to human health and the environment. In unconventional oil and gas operations, a diverse suite of chemical additives—ranging from biocides and surfactants to scale and corrosion inhibitors—adds further complexity and toxicity. Some of these substances, including endocrine-disrupting compounds and persistent organic pollutants, are particularly troublesome due to their ability to bioaccumulate and interfere with biological systems even at low concentrations. Together, this highly variable and hazardous mix makes produced water one of the most difficult industrial wastewaters to manage safely and effectively.

Reference: Veil, J.A. et al., 2004. Argonne National Laboratory Produced Water Study; USEPA 2016; Fakhru'l-Razi et al., 2009, Journal of Hazardous Materials

Possible Recommended Applications for the Water from Oil & Gas Produced Water Treatment Facilities

Due to the numerous possible contaminants in produced oil and gas wastewaters and while produced water can be treated to very high quality — suitable for industrial, agricultural, or environmental uses — final product water is not recommended or approved for human drinking water use, primarily due to:

- The presence of unknown or unregulated trace contaminants
- Persistent chemicals and radionuclides
- Endocrine disruptors and long-term health uncertainties

No US state or federal authority currently permits treated produced water for direct human consumption.

As a result, some investigation was done regarding the permitted applications for treated produced oil and gas wastewater reuse. The Colorado (DJ Basin) is currently the only U.S. basin with legally mandated produced water reuse percentages for fracking operations, as established by HB23-1242 and ECMC rulemaking. The Permian Basin continues widespread internal reuse and industrial applications without a formal mandate. Potable reuse and groundwater recharge for potable purposes remain prohibited everywhere. Surface discharges require NPDES permits under the Clean Water Act — approvals are rare due to stringent water quality criteria. Evaporation ponds are still a common brine management method in both regions, though increasingly scrutinized for environmental impact. For the cities which we have evaluated in the study, the applications are summarized in a table below with the references listed.

Application	Permian Basin (TX/NM)	Denver–Julesburg (CO)	National (EPA/USGS) Regulations
Agricultural irrigation	Limited for non-food crops	Not practiced / prohibited	Case-by-case; rare
Industrial reuse (EOR, dust control, cooling, etc.)	Widely permitted	Widely permitted	Encouraged in E&P
Reuse in fracking operations	Used, but no mandate	**Mandated:** 4% by 2026 → 10% by 2030 → 35% by 2038	Not federally regulated

Surface water discharge	Rare; requires NPDES	Prohibited without NPDES permits	NPDES required; rare
Potable reuse (drinking water)	Prohibited	Prohibited	Not recommended; no approvals
Groundwater recharge (for potable use)	Not practiced	Prohibited	Prohibited for potable use
Evaporation ponds / brine disposal	Widely used	Widely used	Permitted with controls

References:

- *U.S. Environmental Protection Agency (EPA). (2019). Study of Oil and Gas Extraction Wastewater Management Under the Clean Water Act. EPA-821-R-19-001. https://www.epa.gov/sites/default/files/2019-05/documents/oil-and-gas-study_draft_05-2019.pdf*
- *U.S. Geological Survey (USGS). (2018). Produced Waters Database. https://www.usgs.gov/energy-and-minerals/energy-resources-program/science/produced-waters-database*
- *Colorado Energy & Carbon Management Commission (ECMC). (2024). Rulemaking Implementation of House Bill 23-1242: Produced Water Reuse for Well Operations. https://ecmc.state.co.us/*
- *Colorado General Assembly. (2023). House Bill 23-1242: Oil and Gas Produced Water Recycling Requirements. https://leg.colorado.gov/bills/hb23-1242*
- *Veil, J.A., Puder, M.G., Elcock, D., & Redweik, R.J. (2004). A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane. Argonne National Laboratory. https://www.osti.gov/biblio/825459*
- *National Academies of Sciences, Engineering, and Medicine (NASEM). (2019). Produced Water: Opportunities and Challenges for Reuse and Treatment in the U.S. The National Academies Press. https://doi.org/10.17226/25381*
- *Texas Railroad Commission. (2023). Produced Water Reuse and Management Guidance. https://rrc.texas.gov/oil-and-gas/environmental-cleanup-programs/produced-water/*

From Trevi's limited experience exploring oil and gas wastewater treatment projects in the Middle East and executing one project in Oman, usage of treated water from that of oil and gas wastewater treatment is not widely regulated. However for human health purposes, Trevi firmly believes that the recommended applications for water usage in the US should apply similar projects in the Middle East. In addition, another possible industrial application for the cleaned water (since it cannot be used for potable use) could be the production of hydrogen for energy. Trevi has spoken about this application to Middle Eastern companies and the feedback has been very positive.

Site Selection Justification

In this section, we expand more on why we selected the 6 cities for the study.

Dallas–Fort Worth has emerged as a prime candidate for an FO brine concentration plant co-located with a data center because of its acute intersection of oil & gas wastewater, escalating water demand from AI and hyperscale data centers, and intense water scarcity. The DFW region lies adjacent to prolific oil and gas formations—such as the Barnett Shale and the Permian Basin—generating vast volumes of produced water. Meanwhile, it is the second-largest data center market in North America with 663.9 MW of data center space as of end-2023 and it is expected to double the market size by end-2026 demonstrating strong demand from hyperscalers and AI providers.

https://www.cbre.com/insights/local-response/north-america-data-center-trends-h2-2024-market-profiles-dallas-ft-worth
https://www.cushmanwakefield.com/en/united-states/insights/dfw-data-center-report
https://www.nbcdfw.com
nbcdfw.com
fortworthreport.org

Houston, the energy capital of the U.S., combines vast produced water resources with a dynamic data center market and rising water costs—making it another ideal site for an FO brine concentration plant. The city handles significant volumes of produced water from surrounding oil and gas operations. Regional data center capacity is expanding, from 97 MW projected in 2025 to 122 MW by 2030 . These facilities require enormous amounts of cooling water to service high-density infrastructure, especially as AI and hyperscale workloads ramp up, while Moody's has called water scarcity a "growing credit risk" in such markets. Meanwhile, Houston's East Water Purification Plant is undergoing a $4.2 billion overhaul, prompting a 6% water rate increase and ongoing annual hikes. Implementing FO treatment here allows produced water to be upcycled into cooling water reducing demand for costly freshwater and buffering data centers against future water price volatility.

https://www.mordorintelligence.com/industry-reports/houston-data-center-market
https://www.cbre.com/insights/local-response/north-america-data-center-trends-h1-2024-market-profiles-houston

Denver represents a strategic location for an FO brine concentration plant servicing data center cooling need, thanks to its link to the DJ Basin and emerging regional data capacity. Produced water volumes are increasing as hydraulic fracturing activity in the Denver–Julesburg Basin has more than doubled since 2013, with fourfold growth in average fracking water use. Denver's data center footprint, though smaller than Texas metros, is scaling up by multiple software companies acquiring more land or expanding its onsite presence. The city also faces mounting pressure from Colorado River over-extraction and long-term scarcity risk. Cooling demands in Denver-area data centers rely on water-intensive chilled-water or cooling tower systems, similar to the broader industry, which consumes 3–5 Mgal/day per facility An FO plant here could convert local produced water into an alternative cooling water source, reducing reliance on stressed municipal supplies while supporting continued digital growth.

https://www.fractracker.org
https://insideclimatenews.org
https://www.denverwater.org/your-water/water-quality/hydraulic-fracturing

Saudi Arabia, with Riyadh as its political and economic nerve center, stands out as a prime location for developing a forward osmosis (FO) brine concentration plant to process oil and gas produced water for reuse in data center operations. The Kingdom's massive oil industry, led by Saudi Aramco — the world's largest oil company — generates enormous volumes of produced water, a byproduct of oil extraction processes such as water flooding, steam injection, and hydraulic fracturing. This produced water presents both an environmental liability and an opportunity for industrial water reuse initiatives, which Saudi Arabia has begun addressing through high-profile projects like NEOM, aiming for 100% wastewater recycling. Concurrently, Saudi Arabia's data center market is undergoing rapid expansion, propelled by the Vision 2030 economic diversification program, which positions digital infrastructure as a national priority. Major investments from STC, Oracle, and Google Cloud in cities like Dammam and Riyadh underline the country's ambitions to become a regional digital hub. With water scarcity a chronic issue in the arid Gulf region, exacerbated by the water-intensive nature of both oil operations and data center cooling, integrating produced water reuse through FO technology offers a sustainable, cost-effective alternative to desalinated water, which remains energy-intensive and expensive. The alignment of industrial wastewater availability, regulatory support, and surging digital infrastructure needs makes Riyadh an ideal candidate for such a dual-purpose water reclamation and data center cooling initiative.

Mordor Intelligence. (n.d.). Study of data center water consumption in the Middle East and Africa. Retrieved from https://www.mordorintelligence.com
Water footprint assessment of the Middle East. Retrieved from https://waterfootprintimplementation.com

Abu Dhabi's appeal as a site for an FO brine concentration plant stems from its mature oil and gas industry, established wastewater reuse frameworks, and status as a key data center market within the Gulf. Abu Dhabi National Oil Company (ADNOC), one of the largest producers in the region, generates substantial quantities of produced water through enhanced oil recovery techniques, including steam flooding and chemical injection. The emirate has been proactive in wastewater management, with existing infrastructure for reclaiming treated sewage effluent (TSE) used for district cooling and irrigation, laying the groundwork for integrating advanced brine concentration technologies for produced water. Simultaneously, Abu Dhabi's data center ecosystem is expanding rapidly, driven by hyperscale operators like Khazna Data Centers, Microsoft Azure, and AWS, which plan to launch a new region in the UAE by 2026. This growth, combined with the acute water stress faced by the UAE — one of the world's most water-scarce countries reliant on costly desalination for over 90% of its potable water supply — makes water-efficient cooling solutions not just preferable but essential. By converting oilfield produced water into a viable cooling source, the proposed FO plant would mitigate environmental liabilities, reduce dependence on desalination, and enhance the sustainability credentials of Abu Dhabi's digital infrastructure projects.

DatacenterDynamics. (2023). Ooredoo Group to build subsea cable to connect the Middle East. Retrieved from https://www.datacenterdynamics.com
Time. (2023). Water is the new oil in the Gulf. Retrieved from https://time.com
Water Footprint Network. (n.d.). Water footprint assessment of the Middle East. Retrieved from https://waterfootprintimplementation.com

Muscat's selection for a forward osmosis brine concentration plant reflects its strategic submarine cable connectivity, emerging data center market, and untapped produced water reuse potential within its oil industry. Oman, though a smaller oil producer compared to its Gulf neighbors, has actively piloted produced water treatment initiatives through Petroleum Development Oman (PDO), exploring ways to recycle wastewater for industrial and agricultural applications. Muscat's status as a growing digital node is reinforced by the presence of Equinix's ME1 data center and its proximity to several critical international submarine cable systems, including SEA-ME-WE 3, 4, 5, AAE-1, and the PEACE cable, positioning it as an increasingly vital data transit and processing hub. Like its regional counterparts, Oman faces significant water scarcity, with minimal freshwater reserves and near-total dependence on desalination — an expensive and energy-intensive process. Establishing an FO brine concentration facility to reclaim produced water for data center cooling in Muscat would capitalize on existing oilfield waste streams, lower operational water costs for cooling systems, and contribute to Oman's aspirations for sustainable, green infrastructure development. The city's strategic connectivity, supportive regulatory climate for environmental technologies, and existing oil and data infrastructure synergies make it a forward-looking location for this initiative.

DatacenterDynamics. (2023). Ooredoo Group to build subsea cable to connect the Middle East. Retrieved from https://www.datacenterdynamics.com
Time. (2023). Water is the new oil in the Gulf. Retrieved from https://time.com
Water Footprint Network. (n.d.). Water footprint assessment of the Middle East. Retrieved from https://waterfootprintimplementation.com

Key Advantage of Produced Oil and Gas Wastewater Treatment/Brine Concentrations with Forward Osmosis (FO) for Data Centers

1. Efficient Use of Low-Grade Waste Heat

Data centers generate a substantial amount of low-grade heat during operation, typically within the range of 35°C to 50°C. In most facilities, this heat is simply vented to the atmosphere or dissipated through liquid cooling systems. Forward Osmosis (FO) brine concentration processes, which is highly suitable for such saline brines, can capitalize on this low-grade thermal energy, particularly in the regeneration of the osmotic draw solution, which is a critical step in maintaining the system's efficiency. Utilizing waste heat from data centers reduces the need for additional energy inputs, making the FO process more cost-effective and environmentally sustainable as evidenced by the lower cost of water treatment for the FO system utilizing 45 deg C heat source from the data center across all 6 cities evaluated.

2. Reduced Energy Costs for Produced Water Treatment

Managing produced water represents one of the highest operating expenses for upstream oil and gas producers, particularly when dealing with high-salinity streams in remote or regulated environments. FO systems already offer lower energy consumption compared to conventional thermal evaporators. When coupled with the free, otherwise wasted thermal energy from a nearby data center, operational costs for brine concentration and water recovery are lowered even further. This integration improves the overall economics of water management, especially in high-volume or minimum/zero liquid discharge (MLD & ZLD) applications which could be also applied to Case 1 for brackish inland ground water desalination.

3. Sustainable Water Management in Energy-Intensive Regions

For all the 6 cities identified, they are facing significant produced water challenges are also located in regions where data centers are expanding. This alignment creates a natural opportunity for industrial symbiosis. By pairing data centers and FO brine concentration plants, both operations benefit from improved environmental performance and enhanced ESG (Environmental, Social, and Governance) metrics. The approach fosters a circular resource model where waste heat supports water recovery, reducing freshwater consumption and minimizing the environmental footprint of both industries and thus becoming water positive.

4. Enhanced Operational Resilience and Redundancy

Integrating waste heat reuse and water management creates a more resilient operational ecosystem, particularly in remote or off-grid oil and gas production areas. This pairing reduces reliance on trucked-in fuels or standalone thermal systems for produced water treatment, while ensuring a predictable thermal management solution for the data center. The system can also flexibly scale produced water treatment capacity in response to changes in oilfield production rates or water cut, improving operational adaptability and redundancy for both facilities.

5. Potential for Revenue Diversification

Beyond operational efficiencies, this co-location strategy opens opportunities for new revenue streams. Operators may be able to monetize excess waste heat, provide treated water for beneficial reuse applications such as agriculture, mining, or secondary oil recovery, or even commercialize brine concentrates for use in road de-icing or industrial processes. These additional revenue pathways improve project economics and further strengthen the case for integrated FO and data center infrastructure developments.

Conclusion

Combining a Forward Osmosis brine concentration plant with a data center's waste heat system represents a compelling opportunity for industrial synergy. The integration delivers energy efficiency gains, reduces water treatment costs, enhances sustainability performance, and fosters operational resilience. It positions both oil and gas operators and data infrastructure providers to capitalize on circular economy models and evolving ESG priorities. This approach not only improves operational economics but also offers a forward-looking model for industrial co-development in energy-intensive regions.

Appendix 1: Mean Monthly Air Temperatures for 6 cities and the Corresponding COP

Location Data - Monthly Average Ambient Temperature and COP calculations

Location	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Dallas	8.6	10.3	14.6	18.7	23.3	27.8	30.3	30.3	26.9	20.9	14.7	9
HP COP*	2.7	2.7	2.9	3.1	3.3	3.5	3.6	3.6	3.5	3.2	2.9	2.7
Houston	11.7	13.1	17.2	21.3	25.5	28.8	30.5	30.7	28	23.1	17.3	12.6
HP COP*	2.8	2.8	3.0	3.2	3.4	3.6	3.7	3.7	3.5	3.3	3.0	2.8
Denver	-1	1.1	5.3	9.9	14.1	20.1	23.4	22.6	17.8	11.8	4.4	-0.8
HP COP*	2.4	2.4	2.6	2.7	2.9	3.1	3.3	3.2	3.0	2.8	2.5	2.4

Location	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Abu Dhabi	21.50	22.30	25.30	29.60	33.70	35.80	37.40	37.30	35.50	31.90	27.40	23.40
HP COP*	3.18	3.22	3.37	3.61	3.87	4.02	4.14	4.13	4.00	3.75	3.48	3.27
Riyadh	14.00	16.40	20.20	25.20	30.20	33.60	35.60	35.30	32.40	27.30	21.40	16.00
HP COP*	2.87	2.96	3.12	3.36	3.64	3.86	4.00	3.98	3.78	3.47	3.17	2.94
muscat	22.40	23.70	26.90	31.40	35.60	36.80	36.40	35.10	34.10	31.60	26.90	23.40
HP COP*	3.22	3.29	3.45	3.72	4.00	4.09	4.06	3.97	3.90	3.73	3.45	3.27

calculations:

*** COP calculated is ratio of COP (actual)/COP (datacenter)* COP of manufacturer: COP = Thot/(Thot-Tcold) (actual) / COP (datacenter) * COP manufacturer**

* ASHRAE D-CCC23-21.pdf

Data Center Ideal Carnot COP @ 30C:

5.5 — 90C = Avg Hot of FO and 24C = Avg Cold @30C DC (30C+18C)/2=24C — **COP @30C** **3.3**

Data Center Ideal Carnot COP @ 45C: — **COP @45C** **4.4**

7.1 — 90C = Avg Hot of FO and 31.5C = Avg Cold @45C D (45C+33C)/2 = 39C

Hot side = 95 & return = 85 = 90 deg C average

Data Center Ambient COP

(273+90)/((273+90)-(273+T)) — Use to calculate ambient produced water COP

363/(363-(273+T))

Appendix 2: Sample of LCOW Calculations for Dallas, TX

Variable	Value	Unit	Reference
DC Cooling Req	1	MW	Design Point
DC Waste Heat Avail	1.460	MW	From Quote by HP mfg.
FO & RO Plant Size	701	m3/day	Based on heat avail.
FO Plant CAPEX	$ 2,557,664		Derived by Trevi
FO Electrical Energy	4.5	kWh/m3	Assumption tab
FO Thermal Energy	50	kWh/m3	Assumption tab
COP heat Pump with FO	3.3		Calculated from lift and industry quote
FO			
Annual Electricity cost	$ 92,076		Assumption tab & Calculated
Annual FO Thermal Energy Costs (No WH & DC)	$ 328,837		Calculated from Dallas Table below
Annual FO Thermal Energy Costs(30C WH)	$ 308,321		Calculated from Dallas Table below
Annual FO Thermal Energy Costs (45C WH)	$ 231,241		Calculated from Dallas Table below
FO CAPEX	$ 2,557,664		Calculated
Annual FO CAPEX Cost	$ 219,887		Calculated
HEAT Pump CAPEX	$ 500,000		Calculated
Annual HP CAPEX	$ 42,986		From Ref in Document
Annual FO Plant OPEX Cost	$ 256,476		Calculated
UPRO+MVR			
Annual Electricity cost	$ 587,240		Assumptions tab
RO CAPEX Cost	$ 2,732,847		GWI databook
Annual CAPEX Cost	$ 234,948		Calculated
Annual OPEX Cost	$ 327,942		GWI databook
Recovery rate	50%		Calculated
For Dallas			
LCOW FO (no DC)	**$ 3.676**		=Annualized (Electricity Cost + Thermal costs (no HP)+ FO CAPEX+FO OPEX+ HeatPump CAPEX)/1000
LCOW FO (+ DCWH @30 deg C)	**$ 3.596**		=Annualized (Electricity Cost + Thermal costs (w HP @30 deg C)+ FO CAPEX+ OPEX+ HeatPump CAPEx)/1000
LCOW FO (+ DCWH @45 degC + 33 DegC Ret)	**$ 3.295**		=Annualized (Electricity Cost + Thermal costs (w HP@ 45 deg C)+ FO CAPEX+ OPEX+ HeatPump CAPEX)/1000
LCOW UHPRO	**$ 4.497**		=Annualized (RO Electricity Cost + RO CAPEX+ RO OPEX)/1000

Dallas	With 30C DC Heat	$/m3	$/bbl	With 45C DC Heat	$/m3	$/bbl
	LCOW FO (no DC)	$ 3.676	$0.59	**LCOW FO (no DC)**	$ 3.596	$ 0.58
	LCOW FO (+ DC)	$ 3.596	$0.58	**LCOW FO (+ DC)**	$ 3.295	$ 0.53
	LCOW UPRO+MVR	$ 4.497	$0.73	**LCOW UPRO+MVR**	$ 4.497	$ 0.73

Heat Pump Savings with DC Waste heat vs Produced water sourced HP (30C DC)

Location	jan	feb	march	April	may	june	july	Aug	Sep	Oct	Nov	Dec	Annual Energy Used (MWH)
Dallas	8.6	10.3	14.6	18.7	23.3	27.8	30.3	30.3	26.9	20.9	14.7	9	
Ambient HP COP	2.68	2.73	2.89	3.05	3.27	3.50	3.65	3.65	3.45	3.15	2.89	2.69	Ref; ASHRAE, IAE, US DOE sources
COP of DC waste Heat (53% of Carnot cycle (air)	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	Mfg data
FO Energy No DC WH	405.9	359.0	376.0	344.1	332.6	300.2	288.1	288.1	304.5	344.6	363.4	403.9	4110.466
FO Energy w DC 30 deg C	329.1	297.3	329.1	318.5	329.1	318.5	318.5	318.5	318.5	329.1	318.5	329.1	3854.015

Heat Pump Savings with DC Waste heat vs Produced sourced HP (45C DC)

Location	jan	feb	march	April	may	june	july	Aug	Sep	Oct	Nov	Dec	Annual Energy Used (MWH)
Dallas	8.6	10.3	14.6	18.7	23.3	27.8	30.3	30.3	26.9	20.9	14.7	9	
Ambient HP COP	2.68	2.73	2.89	3.05	3.27	3.50	3.65	3.65	3.45	3.15	2.89	2.69	Ref; ASHRAE, IAE, US DOE sources
COP of DC waste Heat (53% of Carnot cycle (air)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	Mfg data
FO Energy No DC WH	405.9	359.0	376.0	344.1	332.6	300.2	288.1	288.1	304.5	344.6	363.4	403.9	4110.466
FO Energy w DC 45 deg C	246.8	223.0	246.8	238.9	246.8	238.9	238.9	238.9	238.9	246.8	238.9	246.8	2890.5