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An Innovative Method of Water Management by Desalinating the Produced Water Using Thermal Renewable Energy

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Abstract

Produced water, which in many cases shows a high degree of salinity, is currently managed using water disposal wells and evaporation ponds. Both methods are conventional and have negative environmental impacts. ARA is adopting a unique and innovative method to manage high salinity produced water in an environmentally sustainable way by extracting potable water from produced water and reducing discharge water volume by at least 50%. For desalination of the produced water an innovative combination of forward and direct osmosis technology is used. This process is driven mostly by thermal energy which is provided to 100% solar thermal collectors.

The structure of the plant is as follows: A solar thermal power plant consisting of 2 desert- and oilfield-proof solar thermal collectors ("HELIOtubes") with thermal energy storage (TES) using pressurized water for nighttime operations (24/7). The solar thermal plant powers an advanced forward osmosis desalination (FO) and brine concentration Direct Osmosis (DO) unit with pre-treatment unit to cope with the challenging produced water.

This project is in the pipeline for implementation. The engineering and the planning design were successfully completed. Two main results are expected from this project, which is: (i) low-cost and low-maintenance thermal power and (ii) desalinated water from the produced water meeting the regulatory specifications.

It is a state-of-the-art system integration engineering based on the simulation of the innovative desert-proof solar thermal plant including TES using 10-year historical satellite-based irradiation data to show optimal use of renewable energy. Lab studies show how low energy consumption pre-treatment of the challenging produced water with its difficult chemical composition can be achieved, allowing membrane-based forward osmosis to be applied even at a salinity level that is 3-times higher than seawater. That leads to high energy efficiency for desalination also at nighttime based on thermal power from cost-effective TES instead of expensive batteries. This system could be considered a game-changer in the oil and gas industry because it introduces a new water management methodology.

Introduction

ARA Petroleum E&P is currently producing hydrocarbons through Early Production Facilities (EPF) from different fields. Drilling for additional oil will continue during 2022 and beyond for the next 20 years. Currently, produced water is disposed of through water disposal wells and evaporation ponds. Produced water volumes have been increasing significantly in correspondence with the expansion of oil production. ARA was facing some challenges in the disposal wells related to surface and subsurface matters. That's why ARA was exploring new innovative technology to introduce a new water management method which is to desalinate the produced water using thermal renewable power.

Through the efforts of ARA E&P to evaluate different technologies and techniques, the team has identified a solar thermal renewable energy system in conjunction with a forward osmosis water separation process that can treat the produced water utilizing a solar system to generate thermal energy for 24/7 with a minimum operating cost throughout the lifetime of the system.

This technology is classified as the highest level of meeting the GHG standards as there will be no CO2 footprint as it uses renewable energy 24/7.

Figure 1 shows the planned plant layout. There will be two outputs from the desalination plant: Freshwater in potable water quality and Brine. Where the freshwater will be used to serve the company's freshwater demand and the extra will be used for agricultural purposes or mixed with water in an injector well to improve the injectivity. However, in the long term, the water demand is expected to increase in ARA and the full output of the water will be used for the company's demand.

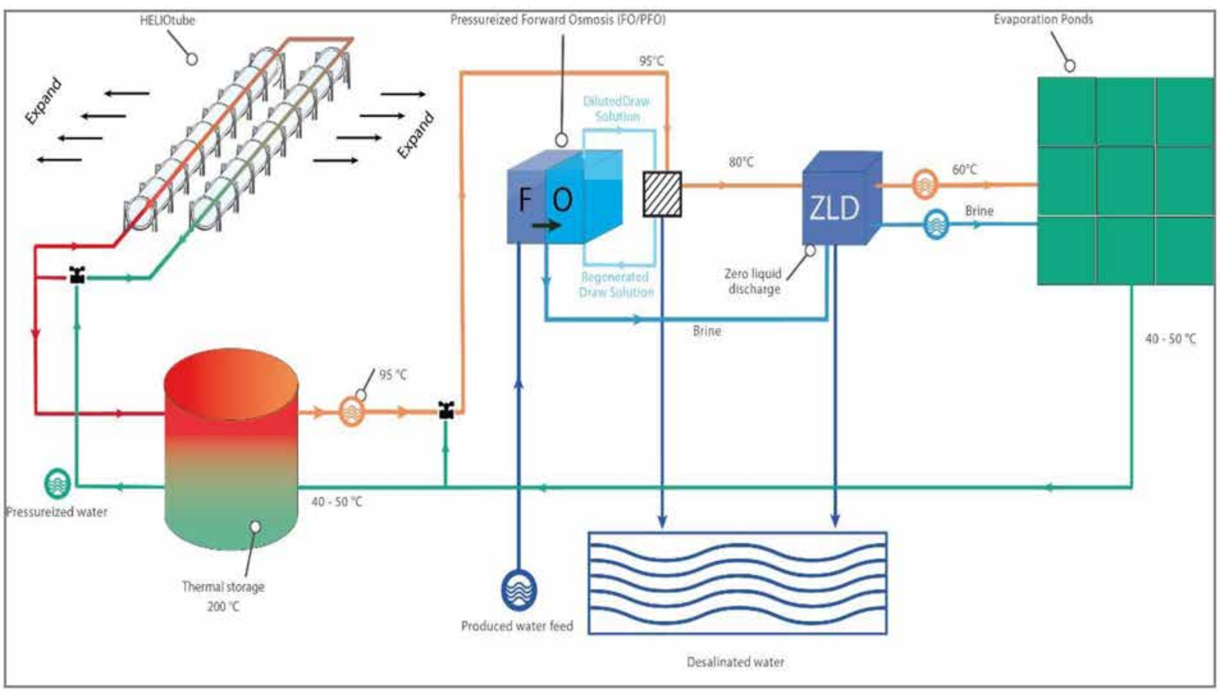

Figure 1—ARA's plant layout of desalinating the produced water using thermal renewable energy. The plant will be specially designed for the use in harsh, arid, and windy desert conditions. The desalination of high salinity feedwater is done in two steps: pressurized FO followed by direct osmosis (DO) as a ZLD stage.

The other output, which is the highly concentrated brine (20% salt), will be collected in the existing evaporation pond where two main R & D studies are ongoing; one related to mineral extractions and the second study related to salt monetization (using salt as a drilling additive). In addition to that, new technologies for lithium/bromine and NaCl, etc., extraction are being researched.

Technology description

The technology is concentrated Solar Thermal Power (CST)-plants that provide 100 % renewable water desalination. CST can be used to power an innovative water desalination technology using osmosis. Forward Osmosis (FO) and Direct Osmosis (DO) can desalinate highly saline and polluted water such as produced water mainly with solar thermal energy. Furthermore, DO potentially allows for extracting almost all the water achieveing a significant reduction of the brine and, thus, the pond size. A 910 kWpth pneumatic solar thermal plant consisting of 2 HELIOtube collectors with 121m length each provides the thermal energy for the desalination process: it includes (a) a highly innovative mirror technology based on Concentrated Solar Thermal Power (CST), (b) a highly cost-effective heat transfer system using pressureised water as heat transfer fluid (HTF), and (c) a low- maintenance thermal energy storage system (TES) allowing nighttime operations of 35m^3 volume with an operating temperature of 180°C using a pressured water tank at 10 bar operating pressure. The desalination system will contain a pre-treatment unit for the produced water and a desalination (FO) and brine concentration (DO) unit. The unit will be integrated with the thermal power to operate the desalination plant. In addition, a fully- automated control system with a live backup will be installed. The software will monitor the data. The system is classified as having low maintenance and cleaning costs due to its unique encapsulation features, rotatability of 300°, and convex shape.

Materials selection and Structure

HELIOtube principle

Figure 2 explains the HELIOtube working principle. In the HELIOtube technology, a cylindrically shaped inflatable structure made from polymer films provides the parabolic trough setup. A mirror film, which divides the cylinder into two air-tight chambers, runs lengthwise through that cylinder. A small pressure difference of about 0.5 mbar between the top and bottom chambers arches the mirror film downward, resulting in a mirror trough that concentrates the incident solar radiation onto a focus line in the upper chamber, where thermal receivers transfer the heat to a Heat Transfer Fluid (HTF). Depending on the differential air pressure between the two chambers the thermal output can be adjusted and optimized. Additionally, the air pressure of about 3.6 mbar inside the solar collector, though very small, makes them self-supporting and stabilizes them against wind impact. The collectors are aligned from north to south and follow the sun movement one-dimensionally from east to west by rotation. Due to the HELIOtube design and material selection, many parts are well able to withstand corrosion. The plastic films per se cannot corrode and at the same time guarantee full of protection for the secondary mirrors and receivers inside the cylindrical structure. Therefore, this encapsulated design is made for the dusty and air-polluted environment typical for the desert and for oil fields. Due to the internal pressure, there is no way for dust and sand to enter into the HELIOtube collector. The internal pressure of about 3.5 mbar is so small that no pressurized air is required for inflation or to maintain it, but only low energy consuming air blower or fans. The air inlet of these specially designed air fan systems applies high quality air filters which are subject to regular cleaning or exchange to keep energy consumption of the fan system low. The PCL-based control system gives notice when the air filters need to be cleaned or changed.

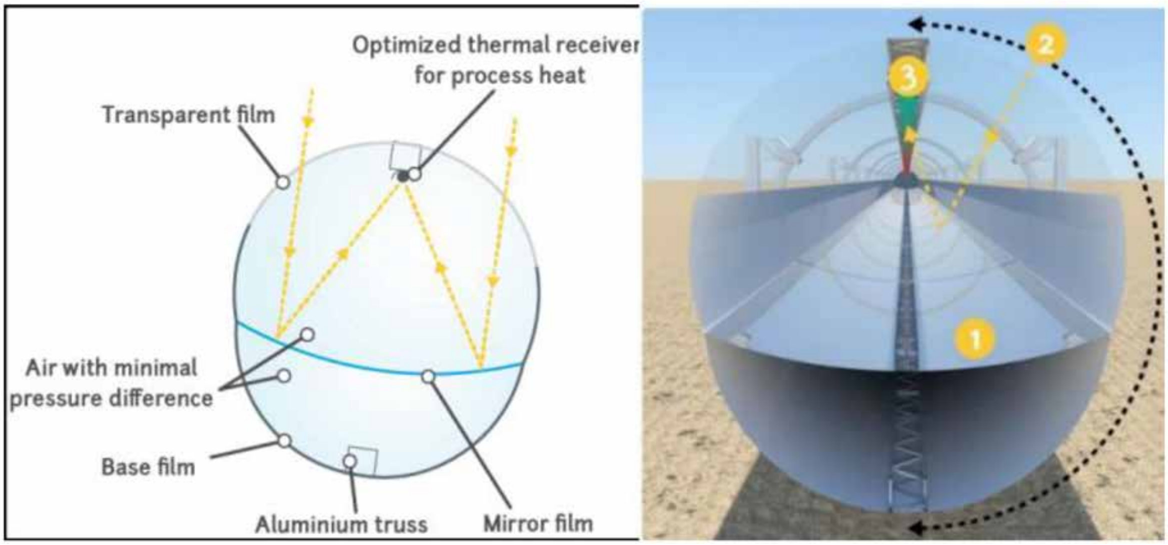

Figure 2—The HELIOtube working principle including the rotation for solar tracking. The mirror film, and the thermal receiver and its insolation and mounting mechanics are protected from dust and sand inside the encapsulated HELIOtube

Water as heat transfer and storage fluid principle: For a remote and environmentally sensitive region such as a field in ARA E&P, the special designed heat transfer and thermal storage system adds to the uniqueness of the plant. Throughout the whole thermal system, form the collectors through the thermal storage tanks into the desalination plant, only pressurized water is used to transfer the heat. Such a system is extremely easy and safe to operate. The operating pressure is 10 bar.

Thermal storage principle

Thermal Energy Storage (TES) systems are accumulators that store the excess thermal energy during the day to be used in the evening and night to keep the desalination process alive. A one-tank design of the TES reduces the operational cost and the required capacity, increasing the efficiency and reducing the capital cost. The thermal storage plays a major role within the coupling of the thermal cycle of a CST plant and FO desalination system. System integration will ensure to make the storage system available for a 24/7 operation with a constant water output. Expected Outcome: A thermal storage system is designed for operating a CST-FO desalination plant at constant water output

Forward Osmosis principle

Table 1 explains the comparison of thermal-driven desalination technologies.Forward Osmosis (FO) is a membrane-based technology using a draw solution to pull the water through a semi-permeable membrane to separate salt and water. FO uses thermal energy to treat the water-rich draw solution in order to separate the water (permeate) from the draw solution, which then is reused. FO combines the advantage of conventional thermal and electrical desalination systems. The desorption of the draw solution is typically thermally driven (~95°C), but in the innovative approach addressed in this project, it does not rely on evaporation and is therefore much more energy efficient) In terms of thermal energy demand FO based desalination driven by concentrated solar thermal power (CST) is 50-57% lower compared to Multi-Effect Distillation (MED) and Membrane Distillation (MD). Compared to Multi-effect desalination system with thermal vapor compression (MED-TVC) and Multi Stage Flash (MSF) the thermal energy demand FO is still 40-50% lower. FO outcompetes MED, MD MED-TVS by up to 45% less electrical energy demand and needs at least 57% less electrical energy than MSF and CST driven RO. Additionally, due to its excellent water recovery ratio the high brine concentration, resulting from an FO plant, facilitates the installation of zero liquid discharge (ZLD) technology, which provides solutions to the growing environmental concerns about brine disposal back into the sea.

Table 1—Comparison of thermal driven desalination technologies

Technology(1)	Typical Operating Temperature of desalination process (°C)	Temperature required at desalination plant battery limit (°C)	Heat Transfer Media Storage Temperature (°C)	Thermal Energy demand (kWh/m³	Electrical Energy demand (kWh/m³)	Recovery Rate (%)	ZLD(4) readiness
MED	66(2)	75	<95	65 - 70	1.8-2.0	30-40	No
MD	66(2)	75	< 95	65 - 70	1.8-2.0	30-40	No
MED-TVC	66(2)	135	160-180	50-60	1.5- 1.8	30-40	No
MSF	112(2)	125	160-180	50-60	3.3-3.5	35-42	No
FO	32(3)	85	160-180	30-35	1.1- 1,5	60 (80)(4)	Yes
CSP-RO	32(3)	NA	> 40Q°C	0	3.1-3.5	38-42%	No

(1) MED: Multi-Effect Distillation, MSF: Multi Stage Flash, MD: Membrane Distillation, FO: Forward Osmosis, RO: Reverse Osmosis, ED: Electro Dialysis

(2) Top Brine Temperature (TBT) can be further increased if feed water is conditioned in Nano Filtration or by acidification

(3) Seawater ambient temperature, e.g. 32°C

(4) 80% for pressure supported FO (PFO)

(5) zero liquid discharge

1. Forward Osmosis FO: 50% reduction of electricity consumption per m³ of desalinated water compared to RO, by shifting the consumption to green thermal energy (easy to produce, easy to store).
2. High Recovery pressurized Forward Osmosis (PFO): Even the standard FO process has a recovery rate of 60% which is already high compared to RO with 42%-48%. But by adding only 1.5 kWh of electrical consumption to the standard FO, pressurized FO (PFO) achieves a recovery rate of 80%! Such a high recovery primary desalination step makes is much easier for the ZLD stages to actually achieve zero liquid discharge.
3. Direct Osmosis (DO) as ZLD stage: The proposed ZLD technology using DO is both highly innovative as well as highly efficient. Normal DO processes required 8- h electrical energy per m³ processed water.
4. Overall recovery rate of 96%: Such a stand-alone desalination plant with its own solar power plant and energy storage for 22.6h average daily operation. Such a facility requires a minimum of infrastructure around it.

Design basis for the proposed pilot plant

Table 2 indicates the geotechnical data and ambient conditions that were studied in detail in the proposed location, and the plant was designed based on these data. All equipment was designed to achieve its rated capacity at a shade temperature of 55 °C and a minimum shade temperature of 5 °C. The equipment will function safely at a maximum shade temperature of 60 °C, but not necessarily at its rated capacity. For the design of air coolers, a design air temperature of 60 °C with a 10 °C approach will be used. The minimum air temperature for the design of air coolers is 0°C. The outlet temperature of the process fluid must be limited to 60 °C in all climatic conditions. The instrument electronics will be able to operate continuously at 60 °C ambient and 82 °C black-bulb temperatures. Electrical equipment and systems shall be designed in accordance with the company standards. Mechanical equipment that is to be stored or on standby, must also be designed to function at the above temperatures. The surface wind velocity is very low with the exception of the occasional intense sandstorms heavily laden with sand and dust particles) during the period from February to April. The prevailing wind is from the southeast. All equipment and instrumentation must withstand the north without any deterioration in condition or performance. Fine dust in these sandstorms can be as small as 2 p. Rain will be infrequent, with negligible annual average rainfall, but when it does rain, it will often be very heavy with severe flooding. Figure 3 represents the history of the last 5 years of Direct Normal Irradiance (DNI) data at the proposed pilot location in ARA. Based on that, data was modeled showing simulated monthly thermal energy output for the proposed pilot plant (MWh) over the last 5 years as per Figure 4. This exercise was necessary in order to forecast the plant's future thermal energy production and its impact on the desalination plant, as shown in Figure 5.

Table 2—Geotechnical Data at proposed location

Ground Temperature (at various below-grade-levels)	Max	35°C @ 800 mm
		38°C @ 650 mm
		40°C @ 500 mm
	Min	20 °C @ 1000 mm
Ground Conductivity (soil conductivity / resistivity to be done under Soil survey)		0.416 W/m°K

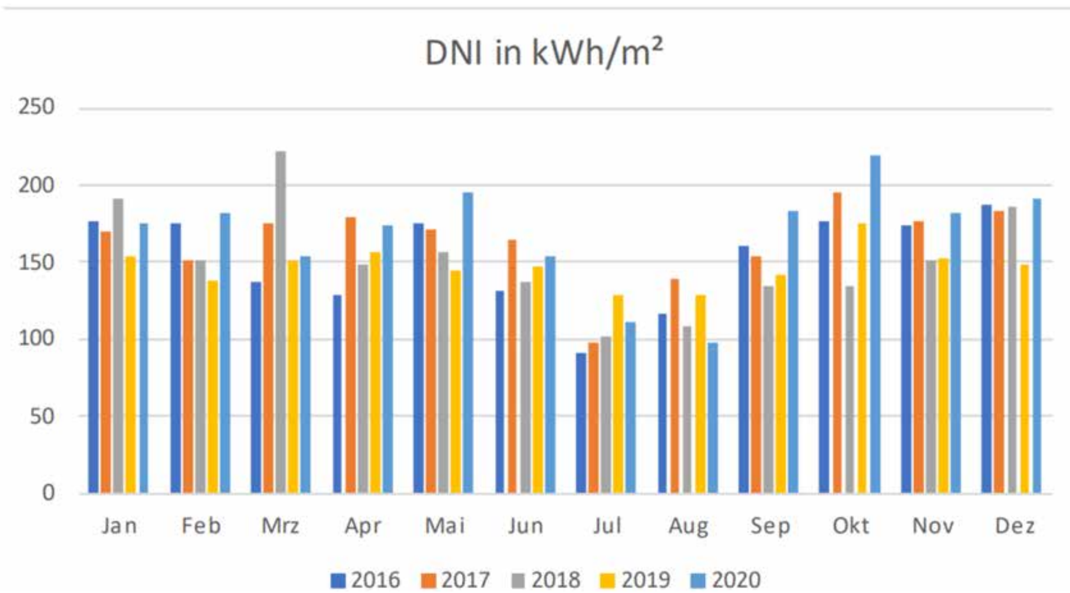

Figure 3—last 5 years Direct Normal Irradiance (DNI) data at the proposed pilot location in ARA

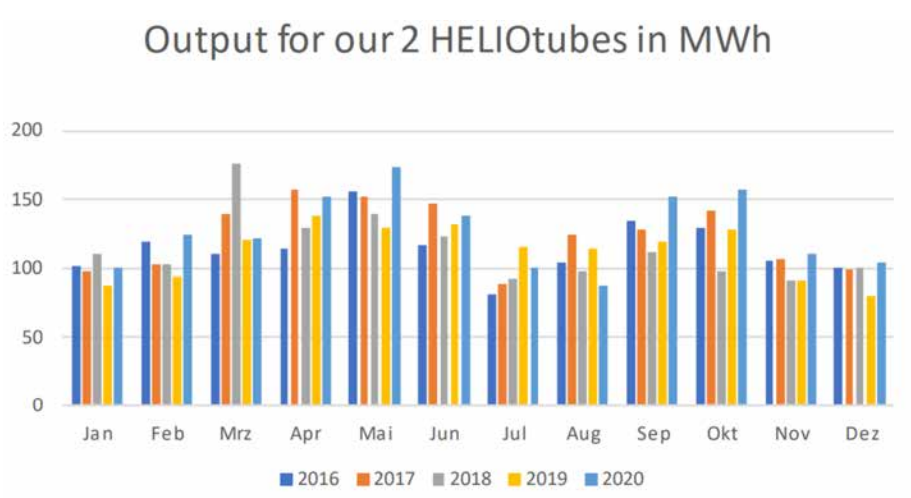

Figure 4—Data model showing simulated monthly thermal energy output for the proposed pilot plant (MWh) over last 5 years

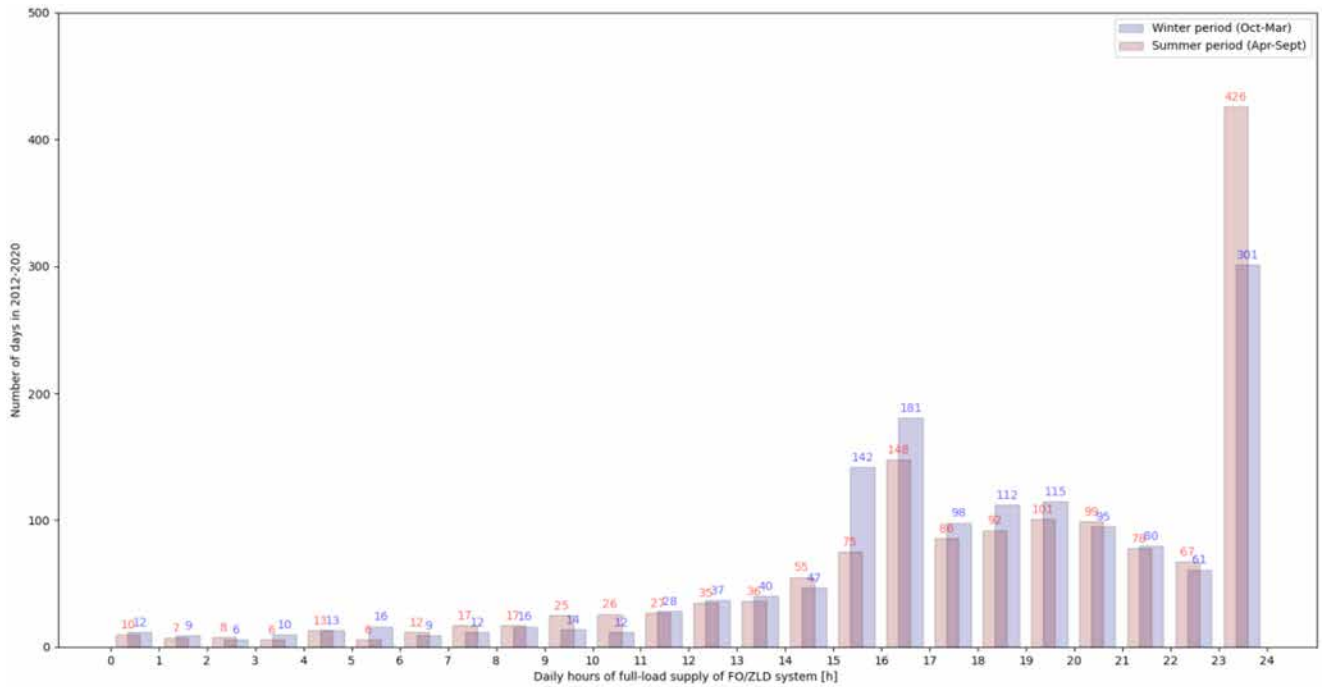

Figure 5—Average distribution differences comparison for " summer and winter" period in hours per day of the Forward Osmosis System running at full power

The ambient conditions are as follows:

- Ambient Air Temperature Maximum shade temperature 60°C
- Mean Summer Temperature (process design) 50°C
- Minimum temperature 5°C
- Mean Winter Temperature (process design) 20°C
- Maximum black bulb temperature 82°C
- Relative Humidity Max 100% Min 4%
- Barometric Pressure Average 97.7 kPa(a)
- Wind Speed Design wind speed (twice/ month) 18 m/s
- Maximum wind speed (1 hr. duration) 22.35 m/s (50 mph)
- Maximum gust (3 second duration) 44.70 m/s (100 mph)
- Rainfall design 25 mm/h
- Average Rainfall annual Negligible

Figure 6 represents the layout configuration of the HELIOtube and the FO desalination system. The plant will be built to fit the relevant environment for the selected field in ARA. As the plant will be built in a very specific environment, the regional variations of ambient conditions may have an effect on the operation of the overall system (CSP, FO and storage), like weather, water temperature and salinity will be evaluated. To increase the ecological performance, the use and combination with existing infrastructure (connection to electrical power, water intake, product water offtake, and brine handling) of the desalination plant will be done. Thermal storage plays a major role in the coupling of the thermal cycle of a CSP plant with an FO desalination system. System integration will ensure the storage system is available for a 24/7 operation with a constant water output. control system for real-time management Predictive controls will be supplied and validated at the site to enhance the flexibility and operability of the lay-out components, with the target of minimum part load operation and quicker transients between different irradiation status. Thermal receiver with secondary mirror combined Heliovis will provide a receiver with lower CAPEX and OPEX for medium-temperature (180 °C) applications such as FO desalination. Furthermore, to shorten the installation time of the collectors in the field, the thermal receiver shall be combined with the secondary mirror of the solar collector, which refocuses the sun's light to achieve higher concentration ratios and thus lower thermal losses. Such a single unit comprising both, the thermal receiver and the secondary mirrors will simplify and speed up the installation process of the collector. air supply system for desert conditions A specific challenge for all solar collectors in the GCC is the desert environment, with its dusty air and sandstorms. The HELIOtube collector was specially designed for use in such environments. This project's demonstrator will provide a real-world solution for the oil and gas industry. The efficiency of the solar collectors does not decrease more than 1% due to dust during the testing and operation phase. Cleaning procedure that is automated This project will be the first implementation of the HELIOtube technology in Oman in ARA and in the desert environment. To maintain the overall performance and durability of the solar collectors, an automated cleaning method for the transparent film will be supported. It will focus on the long-term effect of cleaning, thus avoiding any scratching of the ethylene-tetrafluoroethylene (ETFE) transparent film.

The heart of the system is a Forward Osmosis membrane designed to produce high flux with varying salinity fed to both sides of the membrane. the membrane is operated as a pressurized Forward Osmosis membrane, with flow rates designed so that the hydrodynamics overcomes polarization concentration while operating with large feed salinities.

Feed water, at 100,000ppm, will be concentrated up to 200,000 ppm by a staged PFO osmotic membrane array (for a total concentration of 2 times). To keep within standard pressure vessel ratings, each stage in the process will only concentrate the feed by 40,000-50,000ppm, requiring the multiple PFO membrane stages. All pressure vessels and pumps are commercially available products.

Concentration polarization reduces flux at these high salinity levels, so an increase in salinity causes an exponential increase in membrane surface area. Membrane flux drops by a factor of 8 between 70,000 ppm and 200,000 ppm. The PFO element acts as an electrical energy saving device by exploiting the salinity in the draw solution to increase the feed salinity concentration. Draw solutions are chosen based on the specific feed salt ionic balance so that scaling compounds are not introduced due to reduced diffusion in the membrane. The overall treatment process will consist of three equipment trains on two skids: (1) feed water conditioning and pre-treatment including filtration, and chemical addition for scaling and biological growth, (2) PFO membrane stage; and finally (3) DO membrane system. The feed water pre-treatment consists of a magnetically driven, sealed feed pump, coarse media filtration, chemical injection, and clarification using ceramic nanofiltration NF, with manual water turbidity and TDS monitoring. The system operates at a 50% recovery with feed water of 200,000mg/l.

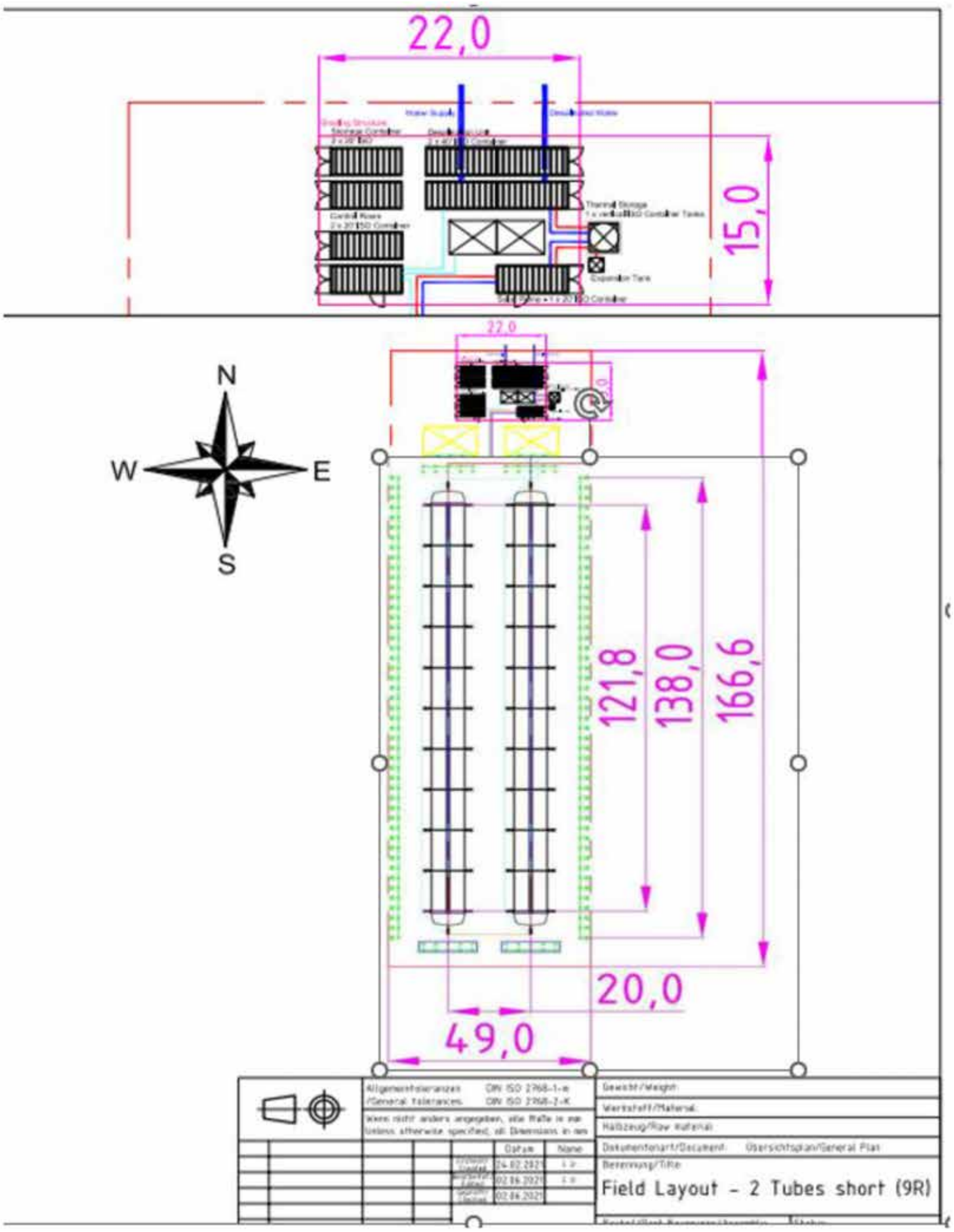

Figure 6—Proposed layout configuration of the HELIOtube system

The product water quality parameters will be set by a combination of the pre-filtration, PFO membrane, and final NF polish membrane elements. The system is equipped with a Programmable Logic Controller Panel (PLC) based control system connected to a display screen A Human-Machine Interface (HMI) for control, system monitoring, and data acquisition. The PLC system is selected to data log the relevant system parameters so that recovery, chemical consumption, and fouling can be evaluated. The overall plant includes all the necessary instrumentation, motor starters, and controls for a complete, integrated system. Figure 7 below shows the overall topology of the system, with its 2 stage PFO-DO topology. The skid includes a single pass nanofiltration (NF) and the staged PFO-DO membrane unit. An anti-scalant and sulfuric acid are dosed to both adjust the isoelectric point on the NF elements and protect the PFO membranes.

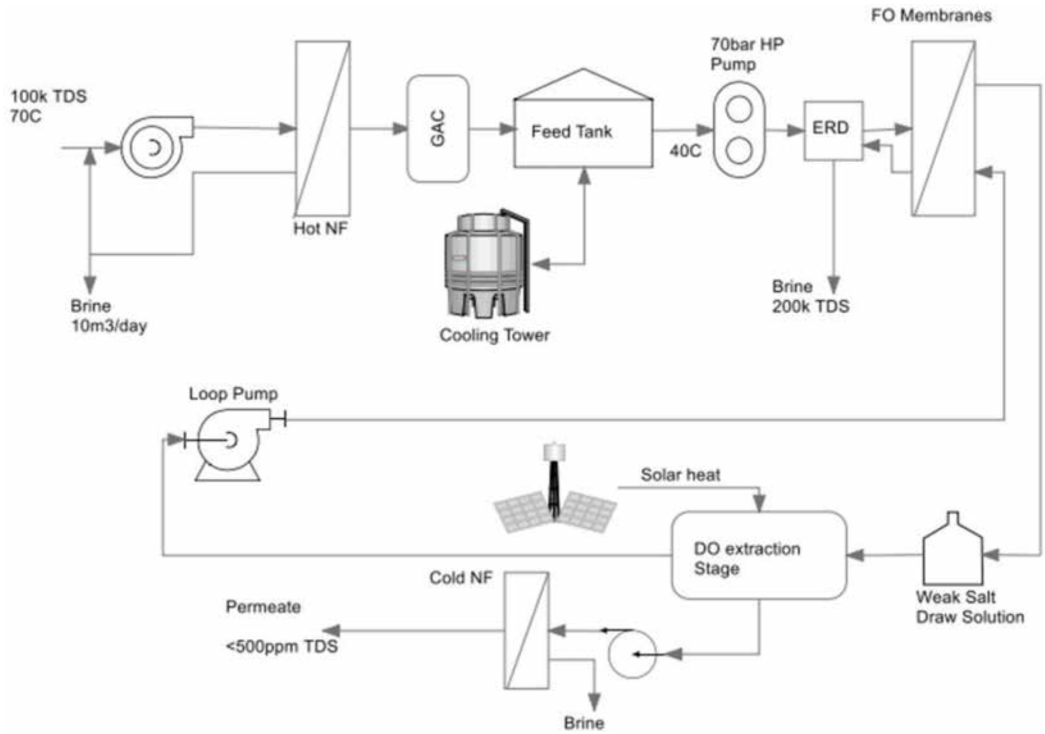

Figure 7—Overall flow of the multi- stage PFO-DO skid

Conclusions

ARA Petroleum E&P is adopting an innovative new technology and engineered solution for handing produced water related to the oil and gas industry, which is one of the major challenges related to production with the possibility for converting produced water into fresh water. The proposed new technology is self-powered and 100% renewable, utilizing solar energy for power generation with minimum environmental impact and with zero CO_2 emissions which is in line with ARA's strategy and commitment to move to renewable energy and to accommodate new technologies with no harm to people or the environment

Several benefits can be achieved from this pilot project, including introducing an alternative method to conventional practices related to produced water handling that is environmentally friendly, economically justifiable, and supplying freshwater for operation working in remote areas. In order to demonstrate the effectiveness of the solar thermal pilot desalination plant (CST) in the context of the oil and gas industry, ARA Petroleum E&P will install and commission the water management system in Oman as the first solar field based on pneumatic CST-technology which will help achieve the highest GHG emissions reduction (eliminating scope 1 & scope 2) and supply clean desalinated water from high saline produced water of 120k ppm for camp usage and drilling applications. We envision this technology has the potential to replace conventional harmful produced water methods. ARA's intention is to scale up the system to handle additional produced water volume in the future once all KPI's are met and verified.

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