Life cycle cost of a hybrid forward osmosis – low pressure reverse osmosis (FO–LPRO) system for seawater desalination and wastewater recovery

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Abstract

In recent years, forward osmosis (FO) hybrid membrane systems have been investigated as an alternative to conventional high-pressure membrane processes (i.e. reverse osmosis (RO)) for seawater desalination and wastewater treatment and recovery. Hybrid FO systems have also shown to be economically feasible in the oil and gas industry to treat high-salinity contaminated streams coming from fracking operations. Nevertheless, their economic advantage to replace conventional processes for seawater desalination and municipal wastewater treatment has not been clearly addressed. This work presents a detailed economic analysis on capital and operational expenses (CAPEX and OPEX) for: i) a hybrid forward osmosis - low-pressure reverse osmosis (FO-LPRO) process, ii) a conventional seawater reverse osmosis (SWRO) desalination process, and iii) a membrane bioreactor – reverse osmosis – advanced oxidation process (MBR-RO-AOP) for wastewater treatment and reuse. The most important variables affecting economic feasibility are obtained through a sensitivity analysis of a hybrid FO-LPRO system. The main parameters taken into account for the life cycle costs are the water characteristics (similar feed water and similar water produced), production capacity of 100,000 m³·d⁻¹ of potable water, energy consumption, materials, maintenance, operation, RO and FO module costs, and chemicals. Compared to SWRO, the FO-LPRO hybrid membrane systems have a 21% higher CAPEX and a 56% lower OPEX due to savings in energy consumption and fouling control. In terms of the total water cost per cubic meter of water produced, the hybrid FO-LPRO desalination system has a 16% cost reduction compared to the benchmark for desalination, mainly SWRO. Compared to the MBR-RO-AOP, the FO-LPRO systems have a 7% lower CAPEX and 9% higher OPEX, resulting in no significant cost reduction per m³ produced by FO-LPRO. For the first time reported, hybrid FO-LPRO membrane systems are shown to have an economic advantage compared to current available technology for desalination, and comparable costs with a wastewater treatment and recovery system. Based on development on FO membrane modules, packing density, and water permeability, the total water cost could be further reduced.

Keywords:

Abbreviation list

AnMBR – anaerobic membrane bioreactor

AOP – advance oxidation process

CAPEX – capital expenses

COD – chemical oxygen demand

EPC – engineering, procurement and construction

FO – forward osmosis

FO-LPRO – forward osmosis - low pressure reverse osmosis

H₂O₂ – hydrogen peroxide

LPRO – low pressure reverse osmosis

MBR – membrane bioreactor

MBR-RO-AOP - membrane bioreactor - reverse osmosis - advanced oxidation process

MF – microfiltration

NF – nanofiltration

O&M – operation and maintenance

OPEX – operational expenses

PV – present value

RO – reverse osmosis

SEC – specific energy consumption

SWRO – seawater reverse osmosis

TDS – total dissolved solids

UF – ultrafiltration

UV – ultraviolet

1. Introduction

Along with the growing demand for fresh water, there is also an increase in the amount of wastewater that needs to be treated adequately to meet public health and environmental discharge regulations. Seawater desalination and wastewater recovery present a promising solution to the increasing pressure on water resources. However, the high costs of desalinating/treating water can impact decision making on implementation of conventional technologies. The use of energy still remains the main component of the costs of these systems.

The energy consumption for desalination using conventional seawater reverse osmosis (SWRO) systems lies between 2.5 and 4 kWh·m⁻³ depending on so many parameters [1,2]. The price of desalinating water by SWRO is nowadays in the range of \$0.5-1 USD·m⁻³, which includes advances in energy recovery devices and membranes with improved performance, but the cost will not continue to decrease with technological developments because equipment and energy costs will increase [1,2]. At the same time, brine discharge regulations are getting more stringent, raising the cost for new projects.

The total cost of water produced by a wastewater recovery and reuse project ranges between \$0.40-1.26 USD·m⁻³ [3], depending on the level of treatment of the influent (i.e. primary or secondary wastewater), and the treatment level required for its reuse (i.e. indirect potable or non-potable reuse, industrial water, irrigation).

Forward osmosis (FO) is a membrane process that can reduce the cost of desalination by extracting water from impaired sources, integrating both processes into a hybrid system. FO utilizes the osmotic dilution concept which relies on the salinity difference between two solutions to drive water permeation through a membrane capable of rejecting solutes, without a draw solution recovery process. In osmotic dilution, a dilute stream becomes concentrated and a concentrated stream is diluted as permeation occurs across a semipermeable FO membrane. By eliminating the energy intensive draw solution recovery, osmotic dilution is truly a low energy FO process [4]. This FO process can then achieve two objectives: i) volume-minimizing treatment of wastewater, and ii) reduction of osmotic pressure of seawater prior to RO desalination. Benefits of reducing the volume of wastewater are reduced energy consumption for treatment, lower volume transported, lower chemical use, and the possibility of harvesting energy (biogas) and nutrients (i.e. phosphates) from the concentrated wastewater more efficiently.

Osmotic dilution can be potentially adapted in a conventional seawater desalination facility as a forward osmosis – low pressure reverse osmosis unit (FO-LPRO) [5], offering the potential for energy and cost savings in an RO facility by lowering the operating hydraulic pressure, enabling to use brackish water RO membranes (BWRO) instead of SWRO membranes which are more expensive, and increasing the water recovery ratio of the whole system (higher flux). Environmental impacts may be diminished by reducing electricity requirements, and also by discharging brines with lower salinity and lower volumes to the aquatic ecosystem. Moreover, reducing the volume of the impaired water offers additional benefits, previously described.

The driving factor for considering implementing a FO-LPRO system versus a reverse osmosis (RO) system (for desalination purposes) or versus an ultrafiltration/nanofiltration (UF/NF) - advance oxidation process (AOP) (for secondary wastewater recovery) or a membrane bioreactor-reverse osmosis-advanced oxidation process (MBR-RO-AOP) hybrid system (for primary wastewater recovery) should be the energy savings related to the capital expenses. FO has been depicted as a near horizon low-energy desalination technology considering that the recovery rate of actual desalination/treatment processes is changed [6].

Energy savings associated with the integrated FO-LPRO system compared to a two-pass RO system are mainly related to the reduction in the osmotic pressure of the partially desalinated water and the hydraulic operational pressure required by the recovery process (i.e. low pressure RO system) to produce fresh water, compared to a traditional RO system. It is clear that lower energy consumption is needed as the dilution rate increases. This, however, requires a higher capital cost for the membrane area. For a hybrid FO-LPRO seawater desalination system, the specific energy consumption (SEC) associated to the FO-LPRO process, after an energy consumption analysis based on a conservative estimate, ranged between 1.3 to 1.5 kWh·m⁻³ using a secondary wastewater effluent as feed and seawater as draw solution (total production capacity of 2400 m³·d⁻¹) [7], which is lower than the energy consumption of conventional SWRO [1,2].

It is important to compare similar processes in terms of influent and effluent water quality. A previous study compares RO for both seawater desalination and tertiary wastewater treatment, which cannot produce water with the same quality [8]. The study reports that capital costs for a plant producing water from seawater are about twice the costs of a plant reusing secondary sewage (not considering the costs of the primary/secondary wastewater treatment facility). Similarly, the operation and maintenance (O&M) costs for producing RO water from seawater are 2 times higher than the cost of reusing secondary sewage. The total life cycle costs for producing RO water from secondary effluent and seawater are \$0.28 and \$0.62 USD·m⁻³, respectively [9]. The final cost of water can differ by a factor of 2 due to inaccuracies (i.e. not considering the cost of treating raw wastewater effluent) in the calculation method.

A report prepared by CH2MHILL in collaboration with Colorado School of Mines [10] did a cost modeling of a FO-RO system for seawater desalination and wastewater recovery in Texas. The results indicated that the use of a FO-RO system is not cost competitive when compared to tertiary treatment of wastewater using a RO membrane unit followed by AOP (ultraviolet (UV) light) for disinfection. However, they identified a critical aspect in the cost of FO-RO hybrid systems: the FO membrane. If FO membrane modules can be commercially produced at a reasonable price (comparable cost to producing an RO module with the same packing density), it is anticipated that use of FO-RO may be viable in the future [10].

A life cycle cost analysis covers the cost of an asset, or its part throughout its cycle life, while fulfilling the performance requirements. It includes construction, O&M [11]. On the other hand, the desalinated water production cost depends on a number of factors affecting both capital (CAPEX) and operational (OPEX) costs. Some technologies have high CAPEX (land, engineering,

unit purchase, transportation, installation, etc. till commissioning) whereas other technologies are higher in OPEX (labor, maintenance and spare parts replacement, energy, and chemicals). The unit cost used in the life cycle cost assessment is USD·m⁻³ of water produced. The differences in water cost estimation, in literature, can be attributed to factors such as differences in (i) fuel or energy cost, (ii) material and construction costs, (iii) feed water properties (such as salinity and turbidity) and (iv) methods of cost calculation [11]. This study used literature information with approximations based on global trends, real data from desalination/wastewater treatment markets, industrial reports and commercially available products.

The objective of this manuscript is to present an accurate and practical life cycle cost comparison between conventional water treatment technologies (i.e. RO, MBR-RO-AOP) and a proposed FO-LPRO hybrid membrane system for seawater desalination and wastewater recovery. A detailed analysis is presented on CAPEX and OPEX of each technology, as well as a sensitivity analysis for the FO-LPRO system on FO membrane flux and FO module cost. Additionally, biogas production from concentrated wastewater is explored as a benefit from the use of such FO system coupled with an anaerobic membrane bioreactor (AnMBR). The discussion focuses as well on the benefits of hybrid systems, the integration of water management sectors (water production and wastewater treatment), and successful cases for wastewater reuse in relation to public perception.

2. Methodology

2.1 Life cycle cost methodology

The comparison between a hybrid FO-LPRO system and conventional water treatment technologies has to be based on the idea that both systems will produce high quality product water and they can be used for the same purpose. In this case, the comparison includes two approaches: *i)* seawater desalination and *ii)* wastewater treatment and recovery.

This work presents a detailed economic analysis on CAPEX and OPEX of 4 different scenarios, detailed in section 2.2. The total cost of each technology is compared based on a production capacity of 100,000 m³·d⁻¹ of potable water, as well as the total water cost per cubic meter. For the wastewater treatment processes, the corresponding population equivalent (P.E.) for a 100,000 m³·d⁻¹ capacity plant is approximately 530,000 P.E.

A sensitivity analysis was made taking into consideration parameters such as the FO membrane pure water flux (L·m⁻²·h⁻¹), FO module cost, and the break-even point between the extra CAPEX of the proposed FO-LPRO technology related to the reduction in OPEX when compared to conventional scenarios.

All costs are shown in present value (*PV*), calculated as:

$$PV = C \frac{1 - (1 + i)^{-n}}{i}$$

where C is the cost, i is the interest rate and n is the lifetime of the project.

2.2 Technologies analyzed

The technologies compared in this manuscript are the following, based on the conventional processes used currently to desalinate seawater and to treat and recover wastewater:

a) Hybrid forward osmosis - low-pressure reverse osmosis (FO-LPRO) process for seawater desalination and wastewater recovery. The feed water for the FO process is considered to be a primary municipal wastewater effluent with an osmotic potential of approximately 0.50 bar. The draw solution is considered to be seawater with total dissolved solids (TDS) of 40,625 mg·L⁻¹ and an osmotic potential of 27.6 bars. The diluted seawater (50% dilution) is then fed to the LPRO unit with a TDS of 20,313 mg·L⁻¹ and an osmotic potential of 13.8 bars [12].

b) Seawater reverse osmosis (SWRO) desalination process. The feed water is considered to be seawater with a TDS of 40,625 mg·L⁻¹ and an osmotic potential of 27.6 bars. A 50% total recovery was considered for a 2-pass RO system [13].

c) Membrane bioreactor – reverse osmosis – advance oxidation (MBR-RO-AOP) process for wastewater treatment and reuse. The AOP was composed of a UV irradiation system with the addition of hydrogen peroxide (H₂O₂).

2.3 OPEX and CAPEX calculations

The calculations on this work are based on the following assumptions: (i) all calculations are present values with a 20 year lifetime for the project and a 6% interest rate [7], (ii) electrical energy cost was defined as \$0.08 USD·Kwh⁻¹ [7], (iii) the calculated electricity consumption for the FO-LPRO system was set to 2.50 kWh·m⁻³ [7, 13], (iv) the recovery of the FO process was set to 50% in relation to initial volume of the draw solution (seawater) and the final dilution to feed the LPRO unit, (v) the AOP was assumed to be a combination of UV irradiation dosages between 300 to 650 mJ·cm⁻² and 6 g of H₂O₂ per m³ [14], (vi) the calculated electricity consumption for the conventional SWRO system was 3.5 kWh·m⁻³ [1, 2], (vii) the cost of each FO membrane module was assumed to be USD1,500, containing a membrane area of 27 m², based on estimations for a real module to be developed by Porifera Inc. [15], (viii) the flux for the FO membrane was considered to be 10 L·m⁻²·h⁻¹ (based on Porifera PFO-150SUB), and the flux for the RO membrane was considered to be 15 L·m⁻²·h⁻¹ (based on RO spiral wound modules SW 30-8040 from Dow Filmtec membranes), (ix) the average relative engineering, procurement and construction (EPC) cost per m³ of the desalination process for the FO-LPRO system was set to USD1,409 [1, 10], and (x) the average relative EPC cost per m³ of the desalination process for the SWRO system was set to USD1,207 [1, 16].

262

263 Table 1 presents the detailed EPC cost for a SWRO, FO stand-alone unit, LPRO and hybrid FO-
264 LPRO desalination plant. The total cost of the proposed hybrid system is higher than that of
265 conventional treatment systems due to the additional need for FO membrane elements,
266 additional costs on pumps and materials.

Table 1 – Engineering, procurement and construction (EPC) cost for a SWRO, FO stand-alone unit, LPRO and hybrid FO-LPRO desalination plant with a total production capacity of 100,000 m³·d⁻¹.

	SWRO		FO		LPRO		FO-LPRO	
Average relative EPC cost per m ³ produced (USD)	1,207		787		1,000		1,461	
Plant capacity (m ³ ·d ⁻¹)	100,000		100,000		100,000		100,000	
	% of total cost	Cost (USD)	% of total cost	Cost (USD)	% of total cost	Cost (USD)	% of total cost	Cost (USD)
Equipment and materials	25.0%	\$ 30,175,000	22.5%	\$ 17,750,000	25.0%	\$ 25,000,000	29.3%	\$ 42,750,000
Membranes	5.5%	\$ 6,638,500	29.4%	\$ 23,148,148	5.5%	\$ 5,500,000	19.6%	\$ 28,648,148
Pressure vessels	1.5%	\$ 1,810,500	-	-	1.5%	\$ 1,500,000	1.0%	\$ 1,500,000
Pumps	7.3%	\$ 8,811,100	6.5%	\$ 5,183,000	7.3%	\$ 7,300,000	8.5%	\$ 12,483,000
Energy recovery	2.0%	\$ 2,414,000	-	-	2.0%	\$ 2,000,000	1.4%	\$ 2,000,000
Piping and high-grade alloy metals	12.5%	\$ 15,087,500	-	-	12.5%	\$ 12,500,000	8.6%	\$ 12,500,000
Others	46.0%	\$ 55,763,400	41.5%	\$ 32,660,000	46.0%	\$ 46,200,000	31.6%	\$ 46,200,000
Equipment + materials + membrane	30.5%		51.9%		30.5%		48.9%	
Construction	69.5%		48.1%		69.5%		51.1%	
Total cost (USD)		120,700,000		78,741,148		100,000,000		146,081,148
Element membrane area (m ²)	28		27		34		n.a.	
Capacity of each module (m ³ ·d ⁻¹)	10.08		6.48		12.24		n.a.	
Water flux (L·m ⁻² ·h ⁻¹)	15		10		15		n.a.	
Total number of elements	9,921		15,432		8,170		n.a.	
Cost per element (USD)	675		1,500		675		n.a.	

n.a. not applicable

The OPEX for SWRO and FO-LPRO units are presented in Table 2. These calculations are based on actual percentages for running desalination plants. Energy consumption represents in average 38% of the total cost of the plant through the lifetime of the project [16].

A summary of the calculation of the total cost and operational expenditures of the MBR-RO-AOP process for wastewater treatment and reuse is given in Table 3.

Table 2 – Operational expenses (OPEX) for a SWRO and FO-LPRO unit in percentage from the total annual cost of a 100,000 m³·d⁻¹ plant [16].

	Percent of total annual cost* (USD)
Energy	38%
Chemicals	5%
Membrane replacement	3%
Labor	3%
Maintenance and others	12%

*The other 39% corresponds to amortization cost for capital expenses

Table 3 – Specific energy consumption (SEC) and engineering, procurement and construction (EPC) cost per m³ of advanced wastewater treatment technologies for wastewater reclamation (MBR-RO-AOP).

Technology	SEC (kWh·m ⁻³)	EPC cost (USD·m ⁻³)	References
MBR	0.114	686	[17-19]
RO	0.910	550	[19, 20]
AOP	0.420	296	[14, 19, 21, 22]
Total	1.444	1,532	

The 4th scenario presented in the next section (results and discussion), referred to as SWRO + MBR-RO-AOP, consists of two projects built and operated simultaneously for seawater desalination and wastewater treatment and recovery, each one with a capacity of treating 50,000 m³·d⁻¹, to sum up a total of 100,000 m³·d⁻¹. By analyzing this scenario, a more accurate comparison can be made with the proposed hybrid FO-LPRO system for desalination and wastewater recovery.

3. Results and discussion

Different scenarios were analyzed for current and proposed wastewater recovery and reuse and seawater desalination technologies. The comparison between OPEX and CAPEX related to the total cost of a treatment plant and the total cost per m³ of water produced is presented, along

with a sensitivity analysis on the cost of the FO membrane, cost of the FO module, and the total savings throughout the lifetime.

The economic cost of a project has a great impact over the final decision on which technology/scenario will be adopted. However, there are other selection criteria that need to be taken into consideration for an integrated water management project in a coastal region. Details on the production of biogas from concentrated wastewater effluent when post-treated are discussed, as well as successful wastewater recovery and reuse projects, final water quality, public perception on direct potable reuse and co-location of seawater desalination and wastewater treatment facilities.

3.1 Life cycle cost analysis and sensitivity evaluation

3.1.1 OPEX and CAPEX: total cost comparison

Figure 1 presents the total cost of the treatment plants for each scenario analyzed, calculated as the sum of the CAPEX and total OPEX throughout the lifetime of the project.

Compared to SWRO, the FO-LPRO hybrid membrane systems had a 21% higher CAPEX and a 56% lower OPEX due to savings in energy consumption and fouling control. Compared to the MBR-RO-AOP, the FO-LPRO systems had a 7% lower CAPEX and 9% higher OPEX. When a simultaneous desalination and wastewater treatment and recovery project was considered (SWRO + MBR-RO-AOP), the CAPEX increases by 13% compared to the proposed hybrid FO-LPRO, and the OPEX is 21% higher.

For the total cost of the project (CAPEX + OPEX), the most economically feasible scenario is the FO-LPRO plant, with a total cost of \$266 million USD for producing 100,000 m³·d⁻¹. The wastewater treatment and recovery scenario has a similar total cost. The total cost of SWRO scenario is 16% more expensive than that of the proposed FO-LRPO scenario. The combined SWRO + MBR-RO-AOP scenario had the highest cost with a total of \$310 million USD, an increase of 17% compared to the FO-LPRO scenario.

Figure 1 – Capital expenses (CAPEX) and operational expenses (OPEX) for the 4 water treatment scenarios analyzed for seawater desalination and wastewater recovery and reuse. Both expenses are shown in present value and summed up throughout the 20-year lifetime of the project to give the total cost. Plant water production capacity: 100,000 m³·d⁻¹.

After obtaining the total cost of the treatment scenarios, the total cost per produced m³ of water can be calculated based on the capacity of the plant(s) for each treatment scenario. Figure 2 shows the total cost of water production per m³. The FO-LPRO scenario has the lowest cost at USD0.636 per m³. The MBR-RO-AOP scenario has a very similar cost (USD0.637 USD per m³). The benchmark for desalination (SWRO scenario) is USD0.737 per m³. The average cost of water for a simultaneous desalination and wastewater treatment and recovery project is USD0.742 per m³, the highest cost for all water treatment scenarios analyzed.

Figure 2 – Total cost of water production per m³ for each water treatment technology assessed based on a plant water production capacity of 100,000 m³·d⁻¹.

From Figure 2, the proposed hybrid FO-LPRO system has a comparable cost to wastewater treatment and recovery scenario (MBR-RO-AOP). The MBR-RO-AOP has the disadvantage of public perception on wastewater recovery for any direct application (i.e. direct potable reuse, irrigation, industrial use, etc.), which may be solved by the approach of a double-barrier hybrid FO-LPRO system against pollutants, using both wastewater and seawater as a source for the production of freshwater.

The results from the calculations in this work show a clear economic advantage in the use of a hybrid FO-LPRO system over conventional desalination technologies such as SWRO. Remarkably, and not reported before, most of the elements in the analysis are based on currently commercially available technology, particularly concerning FO membranes and modules, underlining the significance to the results presented.

3.1.2 Sensitivity analysis based on FO membrane flux and module cost

In order to determine the importance of the FO membrane water flux and the FO module cost in relation to the total water cost for the proposed hybrid FO-LPRO system, a sensitivity analysis was made based on 3 different FO module costs (for the same module type) over 4 different expected water fluxes for the FO membrane. The results of the analysis are shown in Figure 3. Considering a membrane area of 27 m² in each module and varying the FO membrane water flux, it appears that even at low fluxes (5 L·m⁻²·h⁻¹), the water total cost is still below the average

cost for conventional SWRO desalination for the 3 different FO module costs considered. Moreover, water fluxes in several bench-scale studies have shown to be higher than $5 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ when using seawater and municipal secondary wastewater effluent [23].

Figure 3 – Sensitivity analysis on the FO module cost and FO membrane water flux related to the total cost of produced water per m^3 for a FO-LPRO hybrid system for seawater desalination and wastewater treatment and recovery. Plant water production capacity: $100,000 \text{ m}^3\cdot\text{d}^{-1}$.

The FO membrane water flux shows an asymptotic behavior when related to the water total cost (Figure 3). As the water flux increases, the reduction in the water total cost is lower, even when the flux doubles. For an average cost of USD1,500 for the FO module, and considering a flux of $5 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, the cost of each m^3 of water produced is USD0.692. When the flux doubles to $10 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, the water total cost decreases 9% (USD0.637). As the flux increases, the effect on the cost is reduced: when the flux doubles from 10 to $20 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, the total water cost decreases only by 4%.

The module cost shows to highly influence the water total cost when the FO membrane flux is lower than $10 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. For the three different module costs analyzed (USD2,000, USD1,500 and USD1,000), the difference for the water total cost for a flux of $5 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ is 11% and 6% compared to the lowest module price (USD1,000), respectively. If the flux considered increases to $10 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, the difference in cost compared to the lowest module cost decreases to 6% and 3%, respectively. When the flux is set to $20 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, the difference reduces to 3% and 1%. This shows that, for a higher FO membrane water flux, the cost of the module starts to be less

significant for the final water cost of the whole FO-LPRO system. If the FO membrane flux is low ($\approx 5 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$), the cost of the FO module has a higher impact on the total water cost.

Previous estimations set the cost of a FO module as $\text{USD}100\cdot\text{m}^2$ [7], which is approximately double the price considered for the analysis presented in section 3.1. With recent advancements in the field of FO membranes and modules, the cost nowadays is lower and it is expected to reduce further in the future (mass production), which is of great benefit for the economic feasibility of FO-based water treatment technology.

Figure 4 – Sensitivity analysis on the FO module cost related to the total cost of a FO-LPRO hybrid system with a water production capacity of $100,000 \text{ m}^3\cdot\text{d}^{-1}$. A water flux of $10 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ was considered for the FO membrane.

Figure 4 shows the relation between the total cost of a FO-LPRO plant and the cost of the FO membrane module. The module cost represents an important parameter in the calculation of the CAPEX. When a $10 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ water flux was considered for the FO membrane, there was a considerable increase in the total cost of the plant when the module cost doubled. For example, when the FO module cost was $\text{USD}1,500$, the total cost of the FO-LPRO plant was around $\text{USD}146\text{million}$; if the module cost doubles to $\text{USD}3,000$ without changing any other parameter in the calculation, the total cost of the FO-LPRO plant rises to $\text{USD}170\text{million}$, an increase of 16%.

Relating the module cost with the savings in OPEX is critical to understand the importance of the module cost in the overall economic feasibility of the project. Figure 5 shows the total

savings for the FO-LPRO project compared to the SWRO desalination project (considered as the flat line at USD0). The starting period shows negative values, which represents the higher CAPEX required for the FO-LPRO system compared to a conventional SWRO system (Figure 1). As the OPEX is being calculated for every year, and considering that these expenses are lower for the FO-LPRO system than for the SWRO system (Figure 1), the total savings will increase, eventually breaking even approximately at year 6, 8 and 10 (for a 20 year lifetime project) for a module cost of USD1,000, USD1,500 and USD2,000, respectively.

Figure 5 – Total savings throughout the first 10 years of the project, calculated as the difference in total cost (CAPEX + OPEX) between a SWRO desalination plant and a FO-LPRO hybrid plant. Note that in the 3 scenarios (varying the FO module cost), the total savings are positive after 10 years. A linear increase continues over the 20-year lifetime of the project.

Scaling up the production of FO modules is expected to reduce their cost to increase the financial benefits in FO-LPRO projects, reducing the time frame to capitalize the OPEX savings (overcoming the higher CAPEX required). A scenario can be seen where the water total cost may be further reduced and move this technology as a better option to treat and recover wastewater when compared to a MBR-RO-AOP system.

3.2 Biogas production

The hybrid FO-LPRO system proposed in this analysis considers a concentration of 50% for the wastewater effluent. Considering that the initial volume is $100,000 \text{ m}^3 \cdot \text{d}^{-1}$, the volume to be treated after the FO process would be $50,000 \text{ m}^3 \cdot \text{d}^{-1}$. Therefore, a calculation on the amount of biogas that could be produced from a $50,000 \text{ m}^3 \cdot \text{d}^{-1}$ capacity AnMBR was made ($\approx 266,000 \text{ P.E.}$). This is an attempt to quantify one of the added benefits of using a hybrid system that reduces the volume of wastewater to be treated, increasing the concentration of carbon (mixed liquor suspended solids) in the feed, and recovering the energy within the wastewater. Recently Wei et al. 2014 [24] suggested that the addition of an FO concentration step before the AnMBR was a promising way for net energy recovery from typical municipal wastewater in a temperate areas. Table 4 describes the parameters taken into consideration for the calculation of the total energy production ($\text{Kwh} \cdot \text{y}^{-1}$) from an ideal AnMBR.

Table 4 – Yearly biogas production calculation [25, 26].

Capacity ($\text{m}^3 \cdot \text{d}^{-1}$)	50,000
COD in wastewater ($\text{Kg} \cdot \text{m}^{-3}$)	0.72
Biogas production ($\text{m}^3 \cdot \text{Kg}^{-1} \text{ COD}$)*	0.2625
Methane calorific value ($\text{Kwh} \cdot \text{m}^{-3}$)	5.5
Calorific efficiency	0.8
Energy cost ($\text{USD} \cdot \text{kWh}^{-1}$)	0.08
Total COD ($\text{Kg} \cdot \text{y}^{-1}$)	13,140,000
Total methane ($\text{m}^3 \cdot \text{y}^{-1}$)	3,449,250
Energy production ($\text{Kwh} \cdot \text{y}^{-1}$)	15,176,700
Value of energy production ($\text{USD} \cdot \text{y}^{-1}$)	1,214,136

*Average value for an operating temperature between 10-30 °C

The total content of chemical oxygen demand (COD) per year available after processing an average concentrated municipal wastewater effluent is 3 tons, which have the potential to produce approximately 3.5 million cubic meters of methane in a year. Considering the methane calorific value as $5.5 \text{ Kwh} \cdot \text{m}^{-3}$ and the energy cost as $0.08 \text{ USD} \cdot \text{kWh}^{-1}$, the total value of the energy production from the anaerobic bioreactor is around USD1.2million per year. This energy can be utilized to reduce the OPEX of the hybrid FO-LPRO system and reduce the final cost of water.

Wei et al. 2014 [24] have shown that based on the integration of a heat pump and FO concentration technology into an AnMBR for municipal wastewater treatment can result into a net energy recovery for the system. Table 5 compares the net energy recovery ($\text{Kwh} \cdot \text{m}^{-3}$) from municipal wastewater (concentration factor of 1) to the FO-concentrated municipal wastewater (concentration factor of 5 and 10). At 3 different temperatures (10°C, 20°C and 30°C), an increased concentration of 5 times in volume can achieve positive net energy recoveries. A smaller volume of concentrated wastewater can produce energy and it needs less energy to transport it.

Table 5 – Energy balance projection of mesophilic AnMBR integrating heat pump and FO technology (adapted from Wei et al. 2014 [24]).

Feed temperature (°C)	Heat energy consumption (Kwh·m ⁻³)	FO concentrating factor	Concentrated COD (mg·L ⁻¹)	Equivalent methane energy production (Kwh·m ⁻³)	Net energy recovery (Kwh·m ⁻³)
10	7.29	1	500	1.57	-5.72
		5	2500	7.84	0.55
		10	5000	15.68	8.38
20	4.38	1	500	1.57	-2.81
		5	2500	7.84	3.46
		10	5000	15.68	11.3
30	1.46	1	500	1.57	0.11
		5	2500	7.84	6.38
		10	5000	15.68	14.22

3.3 Water quality versus public perception

In terms of water quality, it has been shown that high quality water can be produced, rejecting most of the pollutants and nutrients found in the wastewater and the seawater due to the double barrier system FO-LPRO [5, 27-31]. One of the most successful projects for water reuse is NEWater in Singapore, where the quality of water produced by the Bedok Water Reclamation Plant was found to be better than the water supplied by Public Utility Board (PUB) of Singapore, and also met the water quality standards of the Environmental Protection Agency of the United States and the World Health Organization [32].

Although wastewater treatment is available to achieve recycled water qualities often superior to current potable water standards, public perception of water recycling activities is negative [33]. Some of the problems linked to this negative perception are the lack of infrastructure to supply recycled water, a highly subsidized and very cheap potable water resource, and the lack of community awareness about the limitations of freshwater resources, in particular in urban areas [8], as well as the very high quality water produced by the system.

Even if direct potable reuse is not considered as the main objective of reuse project, there are other uses for which the recycled water can be intended for [34]. As an example, artificial groundwater recharge, indirect potable reuse and industrial process water production are now part of successful wastewater recovery and reuse projects [35]. This first attempts to integrate fresh water production and wastewater treatment and recovery will pave the way towards the creation of direct potable reuse projects in water-stressed areas around the world.

3.4 Wastewater recovery and reuse: successful projects

Although public perception has been one of the major obstacles towards wastewater recovery and reuse, there are successful projects that lead the change in the water management sector, showing the possibilities and benefits of these water recycling systems. Some examples in practice of wastewater recovery are:

i) Groundwater replenishment scheme (Orange County, USA) – used for indirect potable reuse, the system comprises a microfiltration (MF) unit that treats a secondary municipal wastewater effluent, followed by an RO unit and an AOP consisting of UV and H_2O_2 for disinfection [36]. The total cost of water produced is $\text{USD}1.26 \cdot \text{m}^{-3}$ [3]. Capacity: $265,000 \text{ m}^3 \cdot \text{d}^{-1}$.

ii) Direct potable reuse (Windhoek, Namibia) – the system consist of pre-ozonation, coagulation, dual media filtration, main ozonation, biological activated carbon adsorption and a two- stage granular activated carbon adsorption as well as UF prior to chlorine disinfection. The total operational cost of the water reclamation scheme is $\$0.76 \text{ USD} \cdot \text{m}^{-3}$ (including CAPEX and OPEX)[35, 37]. Capacity: $21,000 \text{ m}^3 \cdot \text{d}^{-1}$.

iii) NEWater Project (Singapore) – There are currently four plants producing NEWater at Seletar, Bedok, Kranji and Ulu Pandan. The system utilizes MF, RO and UV to treat municipal secondary wastewater effluent. The water produced is used for industrial and commercial purposes, and a small percentage is now being blend in fresh water reservoirs for further indirect potable reuse [32, 38]. Capacity: $316,000 \text{ m}^3 \cdot \text{d}^{-1}$.

iv) Western Corridor Recycled Water Project (Brisbane, Australia) – the scheme collects effluent from three advanced water treatment plants (Bundamba, Luggage Point and Gibson Island), which incorporate MF, RO and AOP with residual disinfection. The recycled water is used to supply water to power stations, industrial applications and the remaining directed to the main drinking water supply storage (used only as indirect potable reuse when combined water storage is below 40%) [39]. Capacity: $182,000 \text{ m}^3 \cdot \text{d}^{-1}$.

v) Torreele reuse plant for indirect potable reuse (Wulpen, Belgium) – the system was constructed as part of Wulpen wastewater treatment plant. It consists of UF and RO filtration followed by UV disinfection, producing infiltration water that is recharged in the dune aquifer. In 2005 the average cost of water was $\$0.60 \text{ USD} \cdot \text{m}^{-3}$ [40]. Capacity: $6,850 \text{ m}^3 \cdot \text{d}^{-1}$.

As the integration of drinking water and wastewater treatment systems continues, the proposed FO-LPRO system represents a feasible alternative both in terms of price and improved public acceptance due to the double barrier approach towards direct potable reuse scenarios in coastal regions.

3.5 Co-location

A FO-LPRO hybrid system for seawater desalination and wastewater recovery requires co-location of the desalination plant and the wastewater treatment plant, to reduce the cost of transporting one of the two water sources to be treated. This can potentially have an impact on future projects to be built in the same location, either for municipalities or new industrial areas accompanying urbanization in coastal regions. At the same time, a reduction of the treatment plant footprint is feasible with a co-location scenario, possibly reducing the cost of the entire project. Li et al. 2014 [41] have given a good approach towards co-location of hybrid FO-LPRO systems.

4. Conclusions

FO-LPRO has been depicted as a near horizon low-energy desalination technology considering the use of a hybrid system for desalination and wastewater recovery, using the principle of osmotic concentration/dilution. Based on the economic analysis of water treatment systems producing 100,000 m³·d⁻¹ of water presented in this study, it can be concluded that:

- A hybrid FO-LPRO system has lower costs for producing water compared to conventional seawater desalination by SWRO.
 - Compared to SWRO, FO-LPRO systems result in a higher CAPEX, but present a significant reduction in OPEX (56%). As a result of the reduction in OPEX, the total cost per unit of water (USD·m⁻³) for the proposed hybrid FO-LPRO system is lower than benchmark conventional desalination technologies (SWRO).
- The sensitivity analysis showed that the most critical aspect in terms of economic feasibility for these hybrid FO-LPRO systems is the FO module cost.
- The proposed hybrid FO-LPRO system has a comparable cost to wastewater treatment and recovery system (MBR-RO-AOP).
- Additional advantages of hybrid FO-LPRO systems include the reduction in wastewater volume to be post-treated, recoverable biogas production based on anaerobic post-treatment of concentrated wastewater effluent, and the reduction of greenhouse gas emissions compared to conventional high-energy desalination technologies.

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