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Life cycle cost of a hybrid forward osmosis – low pressure reverse osmosis 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. Nevertheless, their economic advantage in comparison to 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 quality characteristics (similar feed water and similar water produced), production capacity of 100,000 m^3 d^{-1} of potable water, energy consumption, materials, maintenance, operation, RO and FO module costs, and chemicals. Compared to SWRO, the FO-LPRO 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 m^3 produced by FO-LPRO. 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.

1. Introduction

Along with the growing demand for fresh water there is an increasing need to resort to non-conventional water sources. 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 (Younos, 2005).

The energy consumption for desalination using conventional seawater reverse osmosis (SWRO) systems lies between 2.5 and 4 kWh m^{-3} depending on many parameters (i.e. intake type, pretreatment, seawater salinity, etc.) (Fritzmann et al., 2007). Typical costs of water desalination by SWRO is in the range of 0.5–1 USD m^{-3}, which has been achieved by advances in energy recovery

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Abbreviation

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
H_2O_2	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

devices and membranes with improved performance; however, a decrease in costs due to technological developments is not foreseen as equipment and energy costs will increase (Fritzmann et al., 2007; Ghaffour et al., 2013). At the same time, brine discharge regulations are getting more stringent, raising the costs for new projects (Lattemann and Höpner, 2008).

Water production costs from wastewater recovery and reuse typically lie in the range between 0.40 and 1.26 USD m^{-3} (Guo et al., 2014), depending on which level the treatment is initiated (i.e. primary or secondary wastewater), and the treatment level required for its reuse (i.e. direct/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. In osmotic dilution, a dilute stream becomes concentrated and a concentrated stream is diluted as permeation occurs across a semipermeable FO membrane (Cath et al., 2010; Hancock et al., 2011). A hybrid systems uses wastewater on one side of the FO membrane and seawater on the other side of the membrane, thus recovering water from the wastewater stream. By eliminating a draw solution and energy intensive water recovery from the draw solution, osmotic dilution becomes a low energy FO process (Shaffer et al., 2015). This FO process achieves two objectives: *i)* volume-reduction 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 (e.g. biogas) and nutrients (e.g. phosphates) from the concentrated wastewater more efficiently. The big opportunity relies in the use of a low-value wastewater effluent, i.e. primary effluent, which at the same time is high in organics for further concentration. In contrast, secondary effluent is a higher-value water with lower organics for biogas production.

Osmotic dilution can also be adapted in a conventional seawater desalination facility as a forward osmosis – low pressure reverse osmosis unit (FO-LPRO) (Valladares Linares et al., 2013a), offering the potential for energy and cost savings in a SWRO facility by lowering the operating hydraulic pressure, enabling the use of brackish water RO membranes (BWRO) instead of SWRO membranes, 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 (Lattemann and Höpner, 2008). Moreover, reducing the volume of the impaired water offers additional benefits, previously described (Wei et al., 2014).

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 compared 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 (Amy et al., 2013).

Energy savings associated with the integrated FO-LPRO system compared to a conventional SWRO 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. Lower energy consumption is needed as the dilution rate increases; however, this requires a higher capital cost for the membrane area (Cath et al., 2010). 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 and 1.5 kWh m^{-3} using a secondary wastewater effluent as feed and seawater as draw solution (total production capacity of 2,400 m^3 d^{-1}) (Yangali-Quintanilla et al., 2011), which is lower than the energy consumption of conventional SWRO.

It is important to compare similar processes in terms of influent and effluent water quality. A previous study compared RO for both seawater desalination and tertiary wastewater treatment, which cannot produce water with the same quality (Dolnicar and Schäfer, 2006). The study reports that capital costs for a plant producing water from seawater are about twice the costs of a plant reusing secondary effluent (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 (Côté et al., 2005). 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. Several studies have shown that an MBR-RO-AOP system is a multi-barrier approach that could be/has been implemented in water reuse projects (Comerton et al., 2005; Gerrity et al., 2013; Pisarenko et al., 2012).