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Lowering desalination costs by alternative desalination and water reuse scenarios

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ABSTRACT

Reverse osmosis (RO) has contributed to a large extent in positioning membrane desalination as one of the best available technologies to meet water demand in dry coastal areas. However, membrane desalination may still be perceived as an energy consuming and high cost desalination technology. Seawater Osmotic Dilution (SOD) may lower the energy consumption and the water cost by decreasing the salt content of seawater; and, at the same time SOD can become a sustainable technology that does not impact marine environments considering that less concentrated brines are discharged into the sea. The main objective of this study was the economical evaluation of SOD for the purpose of decreasing desalination costs. The authors have investigated the attractiveness and viability of SOD opportunities compared with standard RO membrane desalination. Three process configurations (desalination, desalination and reuse, SOD) were defined for a coastal area location, where the possibilities of water availability are limited to mainly the ocean. For each configuration, three different water production capacities (1.000, 10.000, and 25.000 m/day) were studied and evaluated economically in terms of capital expenditure (CAPEX) and operational expenditure (OPEX). The results show that SOD can produce desalinated water with 27% energy reduction compared with seawater reverse osmosis desalination; and that operational costs of desalination can be reduced by 31%. Water volume balances of each configuration demonstrate that SOD has a high potential in dry coastal areas with limited availability of fresh water. For SOD with a commercial price of forward osmosis (FO) membranes at 30–60 US$/m and a membrane flux of 7–14 L/m-h, SOD becomes a viable technology for lowering costs of desalination, with payback times of less than 1.5 years when compared with desalination.

Keywords: Desalination; Forward osmosis; Water cost; Water reuse

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1. Introduction

Membrane desalination in dry coastal locations is the best available technology to supply water demand. Dry coastal locations can be defined as areas where the Palmer Drought Severity Index (PDSI) is in the classification, moderate to severe drought (PDSI < −2) and, geographically, the areas are located next to an ocean. In areas with PDSI of less than −2 and near to an ocean, desalination will be increasingly implemented in the near future [1,2]. Therefore, alternatives for less expensive desalination need to be economically evaluated. Seawater Osmotic Dilution (SOD) can lower the energy consumption by decreasing the total dissolved solids (TDS) of seawater (less osmotic pressure). This study has as main goal the evaluation of SOD for the reduction in desalination costs, both capital and operational. By this, we determine the viability and attractiveness of SOD opportunities compared with seawater membrane desalination. In SOD, forward osmosis (FO) membranes are used for seawater dilution. Seawater is used as draw solution, and treated wastewater is used as feed solution. This technology concept has already been reported in previous publications [3,4].

In cities with water scarcity problems and located in coastal areas, desalination by reverse osmosis (RO) membranes is the preferred method of water supply due to its attractiveness in cost reduction when compared with thermal technology alternatives. Nevertheless, seawater reverse osmosis (SWRO) desalination is still expensive and costs are subject to site, technology, and regional conditions. In SWRO desalination, energy consumption is demanding and varies mainly with water salinity and temperature. It has been estimated that for seawater with TDS of 35,000 mg/l with different alternatives of pre-treatment and with isobaric energy recovery devices, the specific energy consumption (SEC) of the RO system will be in the range 3.0–3.3 kwh/m, and the total SEC of the desalination plant will consume from 3.4 to 4.0 kwh/m [5]. SOD is able to reduce SEC by decreasing the TDS concentration of the seawater.

In dry coastal areas, it is very important to identify the readily available water source, because, in principle, water shortage is the main issue and extra water sources are very limited. Deviations of an initial allocated water demand are the result of increased water uses in industry, municipality, or irrigation. In a coastal area, when that occurs, the only available water source is the ocean. There are several cases where this basic fact of "water balance" has been ignored and problems have emerged regarding completion of demand for municipalities, industries, and irrigation; in coastal areas, the obvious solution is desalination [6–8]. The main objective of this paper is to realistically conceptualize SOD as a viable technology and to evaluate whether SOD offers sufficient economic benefits to provide a strong economic driver to support significant market penetration in the global seawater desalination market.

2. Results and discussion

2.1. Scenarios, water balance, and water ratio

In the first configuration, shown in Fig. 1(a), a SWRO desalination plant and a wastewater treatment plant are presented as facilities located close to each other. Places known for co-siting of desalination plants and wastewater treatment plants are most of the time undocumented or not identified. Co-siting is the common location of desalination facilities with municipal and industrial facilities for wastewater treatment. Co-siting can address cost, energy, and environmental issues hindering construction of new desalination plants [9]. The disposal of treated wastewater has been implemented most of the time separately from installations of desalination. When seawater is in the proximity of a city and depending on the environmental regulations for discharging treated wastewater to the sea, the discharge will be carried out by marine/submarine outfalls. The level of treatment of treated wastewater discharged through marine/submarine outfalls range from primary to secondary treatment mainly. Discharge regulations demanding tertiary treatment are rare but may increase with newer stringent regulations. The current practice of discharging primary/secondary-treated wastewater with marine outfalls is controversial, although their presence is distributed worldwide.

Fig. 1(b) is a description of a simplified water reclamation system with UF and RO membranes. The process is defined as a two-barrier concept, even though UF presents very limited performance for removing various contaminants of concern; specially, organic micropollutants. In the configuration presented in Fig. 1(b), fouling of the RO membrane will become a major issue. Membrane fouling of the RO membrane may be ameliorated by pre-treatment alternatives for fouling control. The use of ozone for pre-treatment, biofilters before/after sand filters/UF, combination of coagulation and UF, use of ion-exchange resins for NOM removal are some examples of pre-treatment technology. The RO permeate is further treated by advanced oxidation processes (AOP) for increased removal of micropollutants. Therefore, the state-of-the-art water reclamation system will be

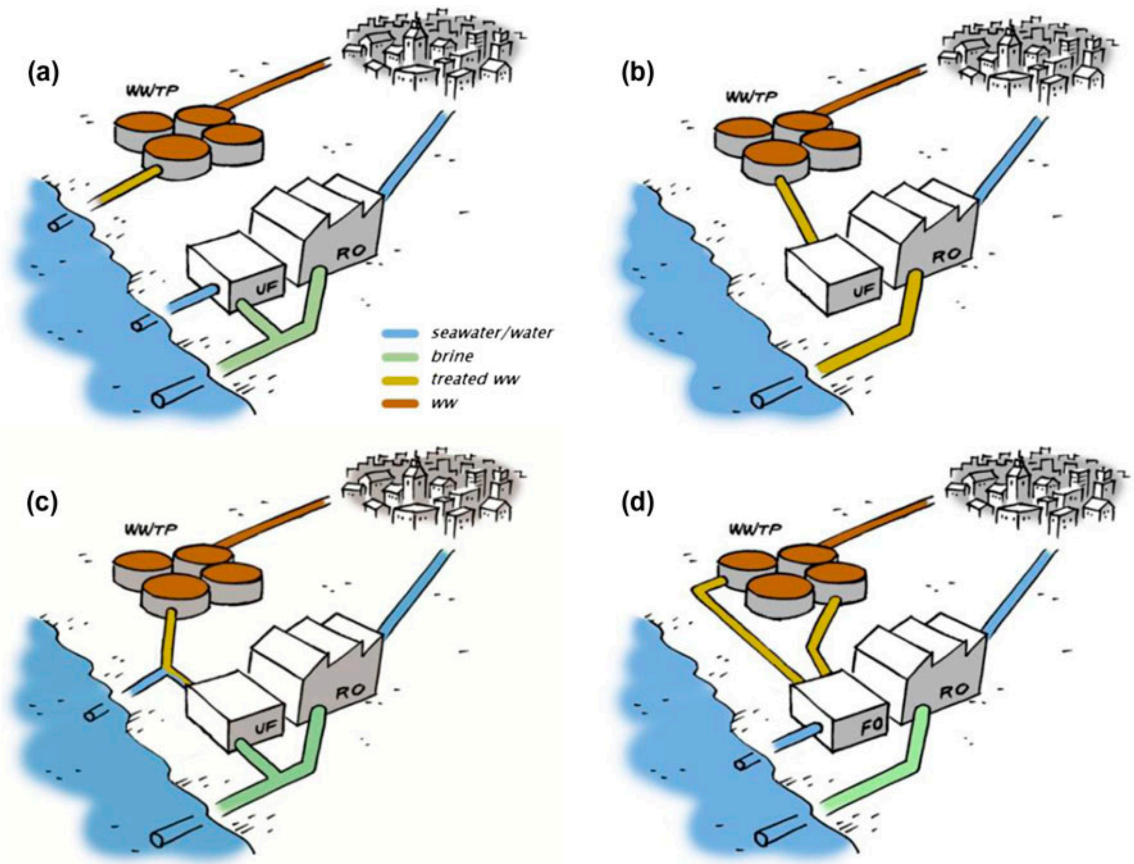

Fig. 1. (a) Desalination, UF–RO with energy recovery, and discharge of treated wastewater, (b) Reclamation of treated wastewater with UF–RO, (c) Treated wastewater mixed with seawater, and (d) Treated wastewater to FO, seawater as draw solution. WWTP (wastewater treatment plant).

defined as: Treated wastewater—Pre-treatment—UF/MF–RO—AOP [10].

Another more theoretical scenario is presented in Fig. 1(c), where treated wastewater is mixed with seawater; and then the diluted seawater undergoes UF–RO treatment. This theoretical approach seems attractive but may result in undesirable fouling of both UF and RO membranes, since the quality of the water can be seriously deteriorated; the deteriorated water (blended waters) result in a mix of inorganic and organic foulants with increased fouling potential. The fouling issue may be resolved by intensive pre-treatment of the water, which will translate into extra costs of treatment. Previous research has presented this approach and emphasized the fact that biofouling control needs special attention [11]. They proposed the use of UV irradiation and modified spacers design in RO modules as ways of controlling biofouling.

Configuration 1d corresponds to the description of SOD. In SOD, forward osmosis (FO) membranes are used for seawater dilution. Seawater is used as draw solution and treated wastewater is used as feed solution. The diluted seawater can be desalinated using less energy, which translates into more economical desalination. It has been demonstrated that FO performs well as an effective barrier against many contaminants, including micropollutants of concern, and further contaminant removal is achieved after RO filtration. It has been hypothesized that an FO membrane is able to remove suspended solids, multivalent ions, natural organic matter, and biodegradable materials [12]. Moreover, FO rejections tests with organic micropollutants (personal care products, pharmaceutical drugs, endocrine disruptor compounds, and other organic constituents) show that high rejections of those contaminants can be achieved by the FO membranes [13,14]. In addition to direct economic benefits due to reduced energy use and production of acceptable water quality, other potential advantages of this desalination approach are: (1) reduced amount of organic fouling and biofouling caused to the RO membrane by transparent exo-polymeric particles (TEP) present in seawater due to pre-treatment and dilution of seawater, (2) increased recovery of the membrane desalination plant, (3) the brine generated is less concentrated and can be discharged without impacting the sea environment [3,15].

Based on the findings of the above-mentioned research work, FO membranes for dilution of seawater with treated wastewater and subsequent RO filtration: (i) is able to produce an acceptable high water quality; (ii) demands less energy consumption; (iii) is able to reduce membrane fouling of RO membranes. Apparently, FO is a viable technology; but its readiness to be implemented needs to be evaluated. The technical conditions for the implementation of SOD production of water are defined and presented in this paper. An important consideration about the scenarios presented in Fig. 1 is that the definition of scenarios per se is not representative of water volumes availability. Therefore, process treatments of scenarios presented in Fig. 1 need a clear definition of water balances. With that respect, water balances are represented in Fig. 2. The starting water balance in a coastal area with limited water availability to satisfy mainly municipal and industrial demands can be represented basically by the water balance presented in Fig. 2(a); where, after a production of 100 water units (wu) as water demand, 20 wu are consumed or lost and become non-returning water, and the remaining 80 wu are discharged as wastewater. The ratio of discharged wastewater to the water demand can define the "maximum" water ratio suitable for water reuse scenarios. However that maximum water ratio may not be realistic for considering losses (evaporation). In that sense, Fig. 2(b) defines an example of water balance where SOD can be implemented realistically where a water ratio of 0.78 is considered, assuming 2% losses of the initial 80 wu. Similarly, Fig. 2(c) defines an example where a combination of desalination and reuse can be implemented realistically, again with a water ratio of 0.78. Contrarily to cases a–c in Fig. 2, a fourth case (d) is presented in Fig. 2(d), where an "unrealistic" configuration of water reuse is presented. In Fig. 2(d), the water ratio is 1.33, which means that "extra volumes" of treated wastewater are required to meet the water demand, which is a "non-existing condition" in dry coastal areas or even in coastal areas with limited

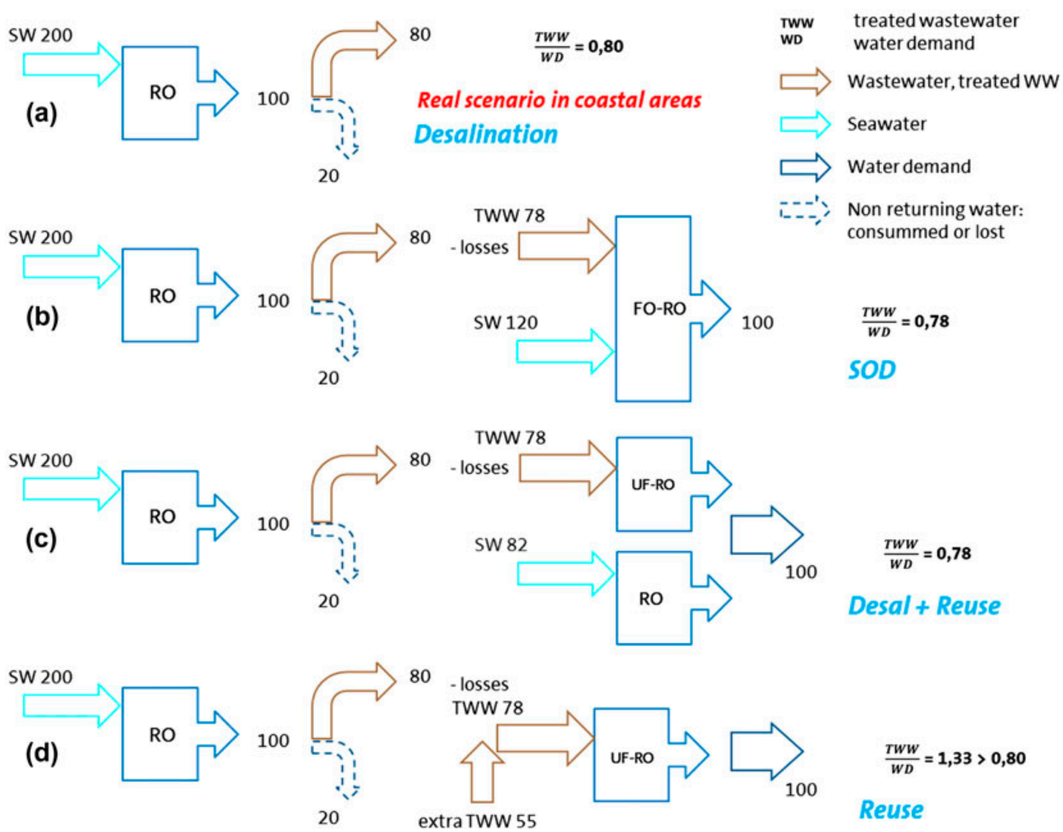

Fig. 2. Water balances with treatment configurations: (a) desalination, (b) seawater osmotic dilution (SOD), (c) desalination and water reuse and (d) "unrealistic" water reuse.

water demand to meet industrial, municipal, and agricultural uses. Independently of the configurations, the water balance should be able to cover the water demand, which means that a water facility must be able to deliver a final water production of 100 wu. It is important to remember that "water must come from somewhere in the first place." Therefore, the only option is desalination and the initial required demand of water can be fulfilled by desalination or alternative desalination like SOD. Covering the water demand by only water reuse from treated wastewater may be a difficult or even impossible endeavor. An "ideal case" will be that where the extra demand of water is supplied by an external source of water, which may be "imported water" from another place (e.g. seasonal availability in other place, a city in close proximity, etc.). However, those "ideal cases" will be difficult to implement, as those conditions are very difficult to find in coastal areas, and thus, 100% water reuse from treated wastewater becomes "unrealistic." In this context, the authors have carried out the following actions: (i) develop conceptual designs for SWRO desalination, combination of desalination and water reuse, and SOD using capacities of 1.000, 10.000 and 25.000 m/day; (ii) develop estimations of CAPEX and OPEX for each design; (iii) develop sensitivity analyses in SOD and estimate payback times; and (iv) estimate water costs.

2.2. Energy, CAPEX, and OPEX

The scenarios reviewed herein are presented in Table 1. All scenarios are compared for the same production capacities (demand of water).

For all SOD cases, the energy consumption of desalination can be reduced by 27%, this is the maximum achievable based on the limitation of the availability of treated wastewater. CAPEX costs for different capacities are presented in Fig. 3(a). CAPEX includes all membrane equipments, pumps, energy recovery, piping, valves, instrumentation, control, electrical work, tanks, and buildings. CAPEX costs do not include taxes, contingency, contractor overhead and profit, engineering and construction management, and general conditions. When analyzing the breakdown of SOD1 CAPEX costs for 10.000 m/d (Fig. 3(b)), a big percentage of the total price corresponds to the FO membranes (34%), but when the membrane price is reduced, the price contribution will be as low as 18% (SOD3, Fig. 3(b)). A similar trend will be observed for 1.000 and 25.000 capacities. The OPEX costs for desalination and water reuse are based on experience and using external sources i.e. Suez-Environment, ACCIONA Agua, Area Metropolitana Barcelona, CH2 M HILL, Hydranautics, and Orange County Water District [5,16–20]. Breakdowns of OPEX costs for SOD (1.000 m/d) are presented in Fig. 4. OPEX includes power, chemicals, membrane replacement, labor and maintenance, spare and wear, and costs of ultrafiltration and cartridge filters. OPEX for SOD includes some conservative assumptions for chemical membrane cleaning (once a month for FO, once every two months for RO) and membrane replacement (every 4 years for FO, every 5 years for RO). From Fig. 4, it is evident that the FO membrane flux and the membrane cost play an important role on defining operating costs. This is especially true since flux and membrane cost will influence membrane replacement. An OPEX decrease of 15% for SOD2 and 22% for SOD3 compared with SOD1 (Fig. 5) can be achievable by either decreasing the membrane price or increasing the membrane flux

A comparison of OPEX costs for all scenarios is presented in Fig. 5. When SOD OPEX reduction is

Table 1
Design considerations for desalination, reuse, and SOD

Name	Seawater, TDS (mg/l)	Diluted seawater, TDS (mg/L)	RO flux, desalination (L/m-h)	RO flux, reuse (L/m-h)	FO flux, SOD (l/m-h)	FO memb. price (US$/m)	Recovery RO/RO/FO (%)
Desalination	35.000	–	15	–	–	–	50/–/–
Desalination & reuse	35.000	–	15	16	–	–	50/75/–
SOD1	35.000	25.000	16	–	7	60[a]	60/–/60
SOD2	35.000	25.000	16	–	7	30[b]	60/–/60
SOD3	35.000	25.000	16	–	14	30[b]	60/–/60

[a]Low volume commercial price.
[b]High volume commercial price.

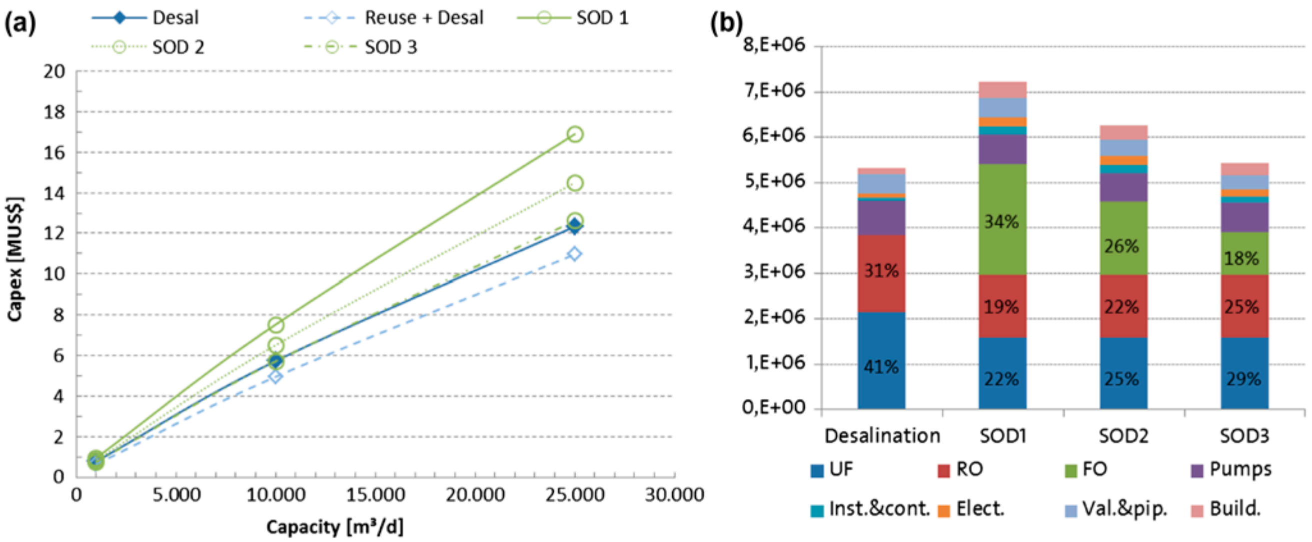

Fig. 3. (a) CAPEX vs. capacity for all configurations and (b) 10.000 m/d, CAPEX breakdown for desalination, SOD1, SOD2, and SOD3.

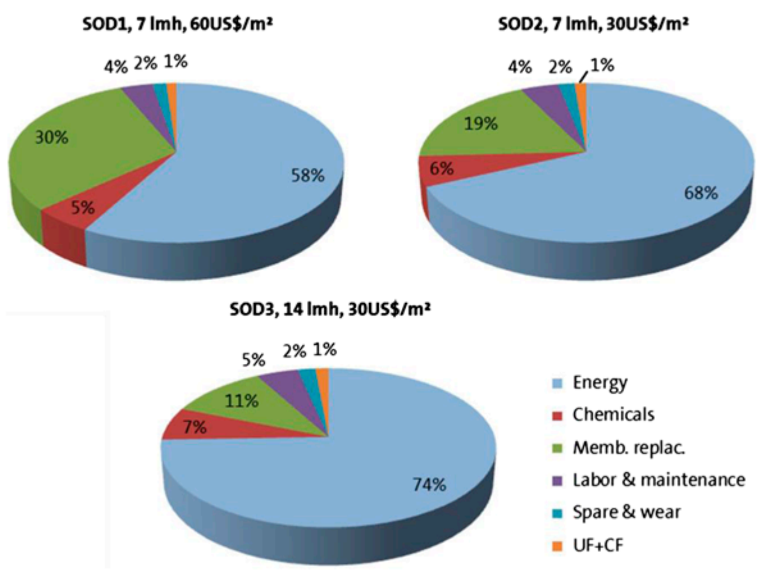

Fig. 4. Breakdown of SOD OPEX costs (1.000 m/d), membrane fluxes and costs correspond to FO.

compared with Desalination OPEX, reductions are 11, 25, and 31% for SOD1, SOD2, and SOD3, respectively. When SOD OPEX reduction is compared with combined desalination and reuse OPEX, reductions are 13 and 20% for SOD2 and SOD3, respectively.

After an analysis of CAPEX and OPEX, payback times were estimated for the comparison of SOD alternatives and desalination. According to Fig. 6, for SOD1, payback times varies according to capacities in a range from 5 to 6.5 years; for SOD2, payback times varies according to capacities from less than 1 year for 1.000 m/d, up to less than 1.5 years for 10.000 and 25.000 m/d. Interestingly, SOD3 presents negative payback times for capacities 1.000 and 10.000 m/d, and less than two months for 25.000 m/d. The flux conditions for SOD2 (7 L/m-h) and SOD3 (14 L/m-h) for SOD may be confidently assumed credible for SOD, since it has been reported that membranes with

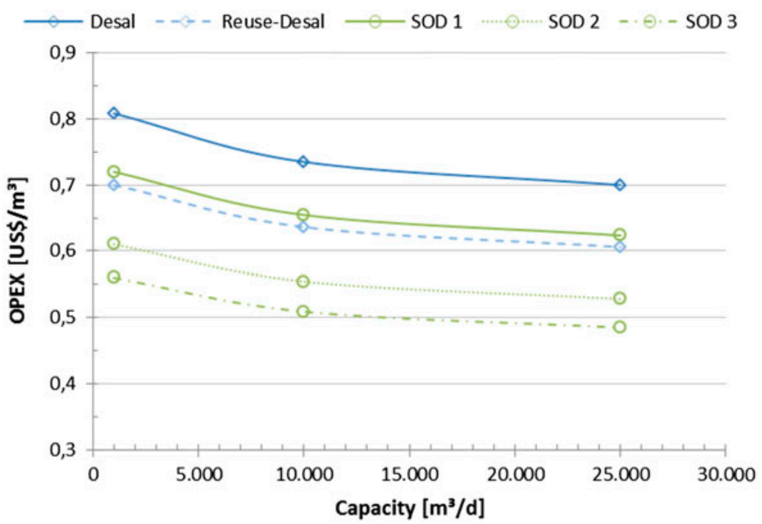

Fig. 5. OPEX vs. capacity for all scenarios.

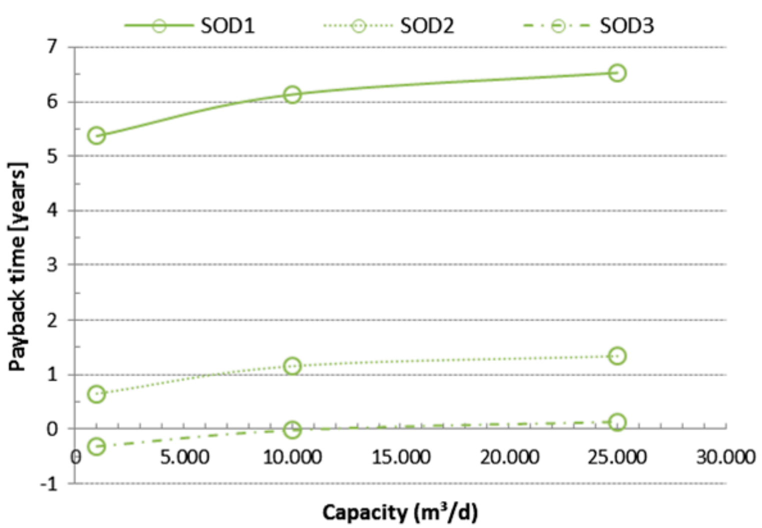

Fig. 6. Payback time vs. capacity for SOD scenarios compared with desalination.

greater fluxes compared with first generation FO membranes (CTA membranes, HTI) are already in the market (HTI, Oasys Water, Porifera). The membrane price condition/assumption for SOD2 and SOD3 (30 US$/m) may seem optimistic but not necessarily when high volume production of FO membranes is expected. The referential commercial price of a desalination RO membrane is 19 US$/m. The flux and membrane price condition for SOD2 (7 L/m-h, 30 US $/m) is equivalent to FO flux of 14 L/m-h and membrane cost of 60 US$/m; a condition that demonstrates that even with a low volume commercial price of 60 US$/m and an achievable FO flux, SOD is technically viable and attractive (less than 1.5 years payback time compared to desalination). The SOD fluxes of FO membranes, in the order of 7–14 L/m-h, are a requirement definitely achievable by existing commercially available FO membranes, which also makes the technology viable for implementation.

In order to allow a complete comparison from an investment point of view, an estimation of the water cost was performed based on CAPEX and OPEX results. The water cost is estimated from the sum of the OPEX per cubic meter of water produced and the

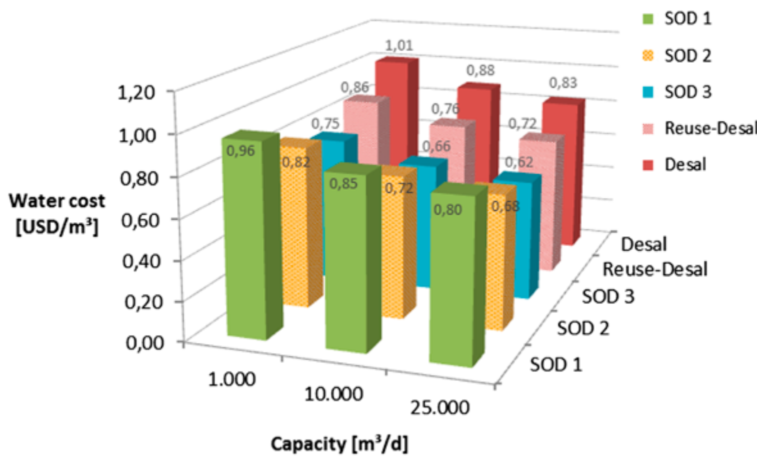

Fig. 7. Water cost (amortization of Capex + Opex cost).

amortization cost of the invested CAPEX (7% interest rate, 20 years assuming public financing, and 10 years will be applicable for private financing). The results of water cost are shown in Fig. 7; the reductions in water costs are 4%, 18%, and 26% for SOD1, SOD2, and SOD3, respectively, when compared with desalination.

3. Conclusions

- Based on the analysis presented in this paper, SOD has been selected as a viable technology of FO for lowering desalination costs.
- It has been estimated that seawater osmotic dilution may realistically offer 27% energy reduction when compared with desalination in dry coastal areas.
- OPEX of seawater osmotic dilution is lower compared with desalination. SOD OPEX may be reduced by 31% OPEX of desalination.
- With commercial price of FO membranes in the range 30–60 US$/m and a membrane flux 7–14 L/m-h, SOD becomes a viable technology for lowering the costs of desalination, with payback times of less than 1.5 years when compared with desalination.
- Water utilities may be able to estimate economic feasibility of SOD based on its specific case of water demand and water balance.

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