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Life cycle cost analysis of desalinating small wastewater flows in the food and beverage industry

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ABSTRACT

Certain sectors of the food and beverage industry that produce saline wastewater (WW) may be required to desalinate their final effluent; whether with the aim of reusing the treated WW or simply to comply with discharge limits. Reverse osmosis (RO) is an energy-intensive desalination process, in which energy consumption is dependent on salinity concentration, flow rate, and desired water recovery percentage. The advent of the energy recovery device (ERD) allows for the recovery of energy from the brine flow in an RO system. However, there is a trade-off between the cost savings from the recovered energy and the cost of a brine disposal. To assess the value of employing an ERD, life cycle cost analysis (LCCA) was conducted using the net present value (NPV) method on a RO system treating wastewaters with similar characteristics to those of a tannery and an aquafarm. The results showed that the value of employing an ERD is highly dependent on the cost of brine disposal, and less on the water that is produced. For inland sites that do not have the option of discharging brine into the sea, the cost of brine disposal can outweigh the economic gains from energy recovery.

Keywords: Wastewater; Reverse osmosis; Energy recovery; Brine disposal; Life cycle cost analysis

1. Introduction

Wastewater from the Food and Beverage (F&B) must be treated prior to discharge into the sewage system or receiving water body. The level of treatment required will depend on the range and concentration of pollutants as well as the assigned final effluent discharge limits. Heavily polluted WWs will generally undergo a series of processes to achieve the desired final effluent quality. These are usually a combination of physical, biological, and chemical unit processes that make up a wastewater treatment system (WWTS); the configuration of which will depend on the type and level of pollutant removal required. Most F&B sector WWs can be treated to acceptable water quality levels with conventional WWTSs such as the widely used conventional activate sludge (CAS) process. However, in addition to the standard WW constituents required to be removed [biochemical oxygen demand (BOD), suspended solids (SS), ammonia (NH_3), nitrate (NO_3^-), and phosphorus (P)], some WWs can contain high concentrations of salt such as tannery WWs which can contain from 30 to 37 g TDS/L (total dissolved solids) DOW [1,2]. The WW discharge limits that pertain to salinity in the European Union (EU) are governed by several directives. The Shellfish directive [79/923/EEC] [3] indicates a range of 12–38 g TDS/L. The variation here relates to habitats of brackish and seawater shellfish species. The surface water directive [75/440/EEC] [4] defines a conductivity limit of 1,000 µS/cm which translates to ~1.5 g TDS/L. While the World Health Organization (WHO) has established guidelines for daily salt intake, there are no specific salinity limits for drinking water other than that concentrations above 2 g TDS/L are unacceptable to taste [5]. Potable water standards set out in the drinking water directive [98/83/EC] define a conductivity limit of 2,500 µS/cm (3.75 g TDS/L) [6]. It should be noted that these limits present only a baseline or guideline level and discharge

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licenses may indicate more site-specific salinity limits that depend on the receiving water body.

The decision to desalinate will depend on several factors, many of which relate to location. Plants located on, or close to the coast may be able to avoid desalination once final effluent salinity concentrations do not exceed the discharge limits. Inland plants discharging into freshwater bodies will be required to desalinate final effluent at salinity concentrations above 1.5 g/L; the alternative to which is to transport final effluent to the sea which in most cases is impractical both from an economic and environmental perspective. However, the cost of investment in, and operation of a desalination system can itself be burdensome, particularly for smaller companies that cannot take advantage of the scale economies associated with desalination systems [7]. Therefore, and great care must be taken to select and configure the most appropriate system for the salinity and flowrate in question in order to minimize costs. There are several desalination processes such as electrodialysis, solar distillation, vapor–compression distillation; however, the reverse osmosis (RO) process is one of the most widely used systems currently in operation and accounts for over 64% of global desalinated water supply [8].

There is some uncertainty regarding the exact date of the first use of the term "reverse osmosis," but it was in 1949 in a report by Dr. Gerald Hassler where he described "salt repelling osmotic membranes" [9]. Today, RO is used worldwide in seawater desalination applications to alleviate pressure on freshwater reserves. Reverse osmosis is widely used in the F&B industry, not only as a desalination process for discharge limit compliance but also as a treatment stage for companies seeking to recycle and reuse WW in upstream production. Haroon et al. [10] demonstrated the potential for RO treated water reuse in the beverage industry for washing and boiler application. Diary WWs treated with RO have been successfully reused for cooling [11], heating, and cleaning [12]. Other application of RO in the F&B industry includes the concentrations of fruit and vegetable juices, and the dealcoholization of fermented beverages [13].

One of the early issues with the RO process was the high specific energy consumption (SEC). In the late 1970s, seawater reverse osmosis (SWRO) plants were reported to consume up to 20 kWh/m^3 [14]. However, since then, advancements in membrane technology and the advent of the energy recovery device (ERD) has seen SEC fall to below 2 kWh/m^3 in some cases [15]. ERDs transfer power from the brine flows in RO systems through a pressure exchange mechanism, reducing the load on the high-pressure pump. Various net transfer efficiencies have been reported in the literature from 82% for centrifugal ERDs, up to 97% for isobaric positive displacement ERDs [16]. One of the problems related to the employment of an ERD is the trade-off that exists between permeate production and energy recovery, or more significantly from a cost perspective, between brine production and energy recovery.

While the production of water and the reduction of energy consumption in the desalination process will improve a company's environmental profile, management of the resultant brine, whether by minimization or direct disposal presents economic and environmental challenges [17]. Current methods of brine disposal for inland desalination plants include evaporation ponds, wind-aided intensified evaporation (WAIV) [18], injection to inland wells [19], surface water discharge, and sewage discharge. However, the latter two options here would defeat the original purpose of desalinating to comply with discharge limits. The chosen method and associated cost of brine disposal are highly site-specific being influenced by geography, land availability, environmental regulations, investment capital (CAPEX), and operational expenditure (OPEX). According to Panagopoulos et al. [20], the cost of brine disposal can range from 5% to 33% of the total desalination cost. For small-medium enterprises (SMEs), the cost of brine disposal may in some cases represent the largest portion of the total life cycle cost (LCC) of the entire desalination process.

The SaltGae Solution (saltgae.eu) is an EU Horizon 2020 research project based on the application of microalgae to treat saline wastewaters from the F&B industry. The project spans several EU States and Israel. Located in three of these countries are three demonstration sites treating dairy WW in Italy, tannery WW in Slovenia, and WW from an aquafarm in Israel. The WWs at all three sites undergo treatment in high rate algae ponds (HRAPs), where the resultant algal biomass is harvested for application in several by-product value chains. The final effluent quality from the process is exceptional; however, those from the tannery and the aquafarm still contain varying levels of salinity that must be removed prior to effluent discharge or reuse. To assess the performance of various RO system configurations and operating conditions a pilot-scale RO rig was designed and developed to treat WWs with similar characteristics to those at the demonstration sites.

2. Methodology

The effluent flowrates, salinity concentration (TDS), silt density index (SDI), and total organic carbon (TOC) for the demonstration sites are presented in Table 1. The DOW[1] ROSA (reverse osmosis system analysis) software was used to select membrane type and quantity, and to determine the required feed pressures. A DOW membrane suitable to treat the flowrate and range of salinities was selected. A six-element, single-stage RO test rig was constructed. The specified water recovery per element was 8% which meant that the total maximum water recovery that could be achieved was 48%. A commercially available class II high pressure pump (HPP) (1.9 m^3/h) and class II centrifugal ERD

Table 1
Final effluent characteristics and flowrate

Parameter	Tannery	Aquafarm
Flowrate, m^3/d	4.8	20
Salinity, g/L	30	5
SDI, n/a	<5	<5
TOC, mg/L	<3	<3

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[1] DOW Water and Process Solutions Inc.

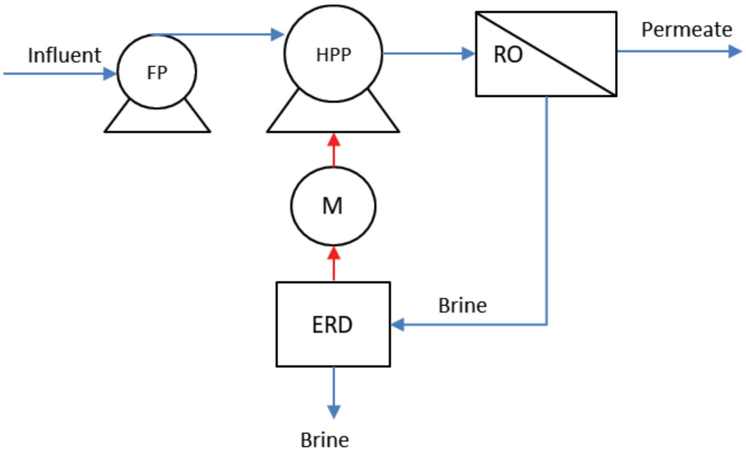

Fig. 1. HPP-ERD configuration RO test rig (FP = feed pump, M = motor).

(1.2 m³/h) unit were commissioned for the test rig. A small pump supplying 0.5 bar pressure was required to maintain feed pressure (Fig. 1).

3. Results and discussion

Steady-state performance data were collected for three different flowrates at the respective salinity levels (Table 2). The maximum flow rate that could be achieved with the HPP was 1.7 m³/h. Water recovery percentages ranged from 33.19% to 36.71% with the highest values being achieved at 1.2 m³/h for both salinity levels.

3.1. Energy performance at 30 g TDS/L

The SEC[2] values ranged from 2.61 to 3.37 kWh/m³, increasing with respect to flowrate. The percentage of total power recovered was highest (52%) at 0.6 m³/h, and lowest (41%) at 1.7 m³/h. A system performance index (SPI) is used in these analyses to describe the ratio of hydraulic power produced to electrical power supplied. The highest and lowest SPIs were observed at 1.2 and 1.7 m³/h, respectively. A summary of the power and energy data is provided in Table 3.

3.2. Energy performance at 5 g TDS/L

The SEC values ranged from 1.64 to 2.12 kWh/m³, increasing with respect to flowrate. Daily energy consumption cannot be applied at 0.6 m³/h as the hourly flowrate is too low to treat the daily influent flowrate. The SPI values of 0.59 and 0.61 are below what might have been expected for a system operating without energy recovery. The negative mechanical power recovery values were observed at low initial pressures (Table 4). The system exhibited negative ERD efficiencies at TDS concentrations below 8.0 g/L.

The maximum water recovery achieved in testing was 35.01% (tannery) and 36.71% (aquafarm), which meant that the lowest brine[3] production percentages achieved were 64.99% and 63.29%. Based on the daily flowrates this equates to 3.03 and 15.82 m³/d of brine to be disposed of for the tannery and aquafarm respectively. Both demonstration sites are located inland, some distance away from the coast, and therefore brine discharge into the sea is not practical either

Table 2
Steady state performance data

Parameter	Values					
Feed flowrate, m³/h	0.6		1.2		1.7	
Feed salinity, g/L	5	30	5	30	5	30
Feed temperature, °C	18.07	20.67	18.41	20.98	19.12	21.34
Feed pressure, bar	8.39	35.68	13.25	40.84	17.51	45.49
Recovery, %	33.71	33.19	36.71	35.01	36.09	35.2
Salt rejection, %	97.76	98.63	99.20	98.89	99.44	99.08
Permeate salinity, mg/L	115.7	415.6	66.52	345.5	29.38	285.0
Permeate pH	7.26	6.88	7.14	7.19	6.82	7.25
Brine salinity, g/L	7.83	45.53	8.45	48.45	8.89	48.31

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[2] Specific energy consumption values presented throughout this document refer to kWh/m³ of permeate.
[3] The term "brine" in the context of this study refers to all non-permeate flow regardless of salinity concentration.

Table 3
Summary of power and energy data at 30 g TDS/L

Parameter	Values		
Feed flowrate, m^3/h	0.6	1.2	1.7
Hydraulic power required, kW	0.55	1.30	2.15
Electrical power supplied, kW	0.52	1.13	1.96
Mechanical power recovered, kW	0.26	0.56	0.80
Percentage of total power recovered, %	51	50	41
Electrical energy, kWh/d	4.16	4.52	5.53
Specific energy consumption, kWh/m^3	2.61	2.69	3.27
System performance index	1.07	1.15	1.10

Table 4
Summary of power and energy data at 5 g TDS/L

Parameter	Values		
Feed flowrate, m^3/h	0.6	1.2	1.7
Hydraulic power required, kW	0.13	0.43	0.78
Electrical power supplied, kW	0.30	0.72	1.30
Mechanical power recovered, kW	–0.04	–0.02	–0.07
Percentage of total power recovered, %	–14	–3	–5
Electrical energy, kWh/d	n/a	15.06	19.12
Specific energy consumption, kWh/m^3	n/a	1.64	2.12
System performance index	n/a	0.59	0.61

from an economic or environmental perspective. The lowest cost that could be sourced from the literature for brine disposal was €6/m^3 [21]. It is, therefore, questionable under the given site-specific conditions whether or not the economic gains from energy recovery outweigh the cost of higher brine, and lower water production. In the analysis of the aquafarm WW, the resultant brine salinity was only slightly higher than the original feed flow salinity. It is reasonable to assume that the brine flow could be recirculated and blended with the influent flow through several iterations up to the feed pressure constraint for the given system configuration; thus, reducing the brine volume and subsequent disposal cost to a minimum. The high initial salinity concentration of the tannery WW does not allow for brine recirculation within the given constraints. To assess the value of brine recirculation and ERD implementation, scenario analyses, and LCCA were conducted for both demonstration sites with the ROSA software using the HPP, ERD, and motor efficiencies derived from the initial set of experiments.

3.3. Scenario analyses

High pressure pump efficiencies used for the non-ERD system configurations were based on experimental results from the testing of a novel volumetric positive displacement HPP designed and developed as part of the SaltGae project (Fig. 2). Figs. 3 and 4 present, respectively, the RO system configurations for the aquafarm with and without energy recovery. A brine recirculation pump drawing an additional 10 W of power was required for both configurations. A percentage of the brine is returned to a transfer tank for blending with the influent flow. The power required for the mixer was assumed to be 5 W/m^3 [22]. Microsoft Solver (Excel 2016) was used to determine the optimum brine recirculation rate within the system constraints; firstly, to minimize final brine volume, and then the total daily energy consumption. The minimum flowrate possible for the HPP-ERD configuration to treat a flowrate of 20 m^3/d with a brine recirculation flow of 84% of total brine flow was 1.7 m^3/h over a 24 h operation period. Fig. 5 presents the tannery RO system configuration without energy recovery.

4. Results

The SEC value for the 30 g TDS/L non-ERD scenario (Scenario 2) was 37% higher than Scenario 1 at 3.69 kWh/m^3; however, water recovery was also 37% higher at 48%, and subsequently, brine flow was 20% lower (Table 5).

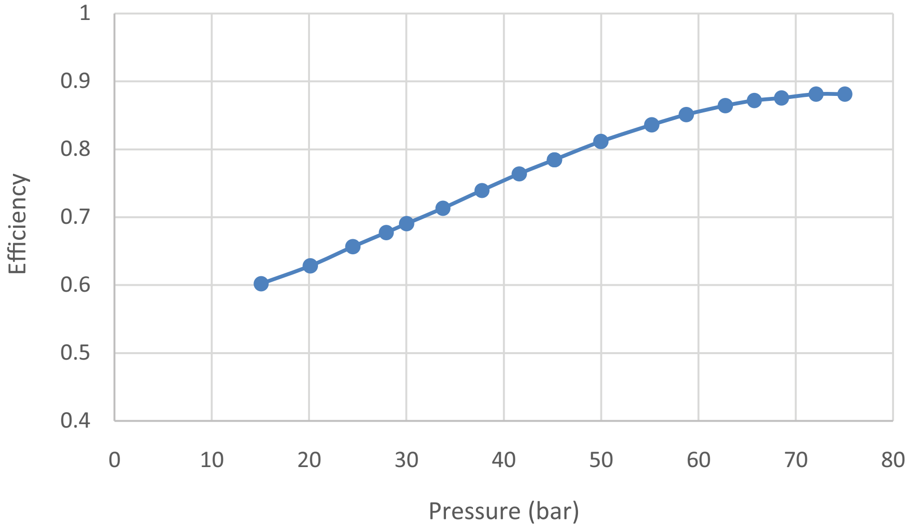

Fig. 2. SaltGae HPP efficiencies.

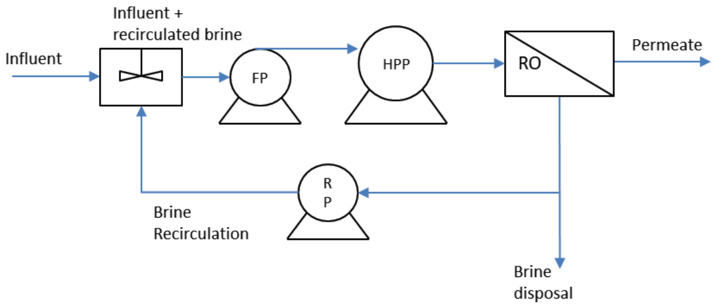

Fig. 3. Aquafarm RO configuration with brine recirculation and without energy recovery.

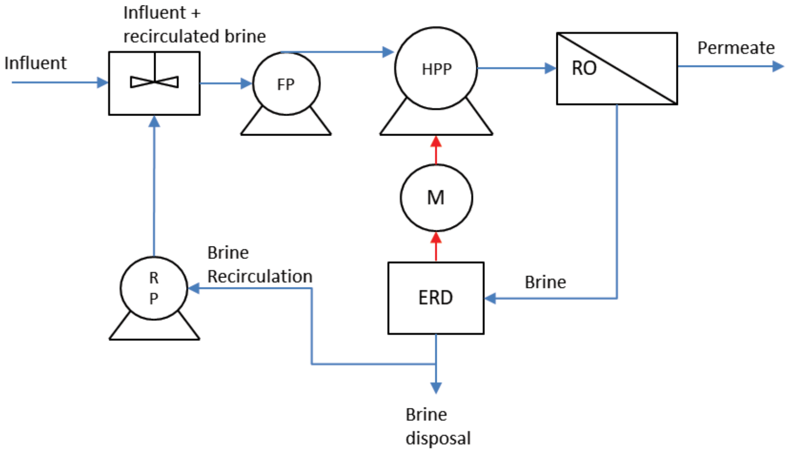

Fig. 4. Aquafarm RO configuration with brine recirculation and with energy recovery.

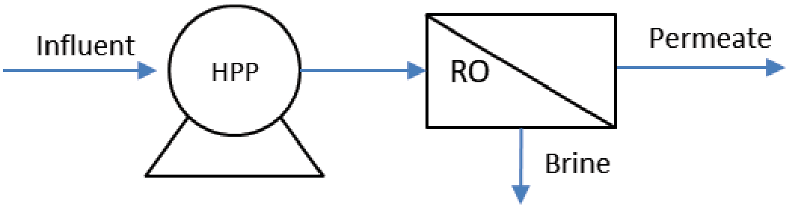

Fig. 5. Tannery RO configuration without energy recovery.

As would be expected, the SPI for Scenario 2 was lower (0.77) than the ERD scenario (1.15). The contrasting system performances of the 5 g TDS/L scenarios (Table 6) were much less significant. SEC values were very similar, with the non-ERD system (Scenario 4) higher by only 6%. Similar trends were observed for total water recovery ($\Delta < 10\%$), and SPI ($\Delta < 4\%$). The similarity in the performance values between system configurations can be attributed to the low ERD efficiency at lower salinity and subsequent pressure levels. While recirculation of the brine did increase the pressure levels, they did not exceed much more than 25 bar. The maximum ERD efficiency achieved was 37% and performed to the point where the SPI achieved a value greater than 0.8. However, recirculation of the brine flow was limited by the flowrate capacity of the pump in that a maximum of 84% of the brine could be recirculated in a single day. It was determined that a pump capacity greater than 2.11 m^3/h would allow 100% of the brine to be recirculated. This would contribute to a pressure increase, but it is doubtful that it would increase the ERD efficiency enough to produce an SPI greater than 1.

4.1. Life cycle cost analysis

4.1.1. Net present value

The net present value (NPV) method was used to determine the LCCs of each scenario. The single present value (SPV) formula applies to one-off payments that occur sometime in the future such as pump and membrane replacements.

$$\text{SPV} = \frac{C_0}{(1+d)^n} \tag{1}$$

where C_0, is the original cost at the base year, n is number of years from the base year, and d is the applied discount rate. Annually recurring OPEX is calculated with the uniform present value (UPV) formula [Eq. (2)]. In this study the OPEX is limited to brine disposal, and water recovery is treated as a negative cost or revenue.

$$\mathrm{UPV}_{\mathrm{OM}} = \sum A_{0,i}\left(\frac{(1+d)^n - 1}{d(1+d)^n}\right) \tag{2}$$

where $A_{0,i}$ is the annual recurring cost of the O&M element i, at base year 0. In the study conducted by Kalbar et al. [23], recurring energy costs were treated separately from other O&M costs. This relates to the volatility in the cost of energy. In recent years, changes in the cost of energy have not aligned with construction cost indices (CCIs), and a separate discount rate for energy should be used [Eq. (3)].

$$\mathrm{UPV}_E = A_0 \frac{(1+d)^n - 1}{d(1+d)^n} \tag{3}$$

The total LCC is given by Eq. (4).

$$\mathrm{LCC} = \sum\left(\mathrm{SPV} + \mathrm{UPV}_{\mathrm{OM}} + \mathrm{UPV}_E\right) \tag{4}$$

4.1.2. LCC parameters and values

The LCC parameters and associated values used in the analysis are presented in Table 7. A 30 y lifetime is defined for the system as it is assumed that all system components can be replaced when necessary. The energy discount rate is based on the communication from the European Commission [24]. The lowest brine disposal cost that could be sourced was the "Wetted-Fin Method," which when converted to present-day Euro was €6/m^3, and 65% lower in cost on a per-unit volume basis than the spray evaporation method examined in the same study [21]. The value of water produced is assumed to be equal to that of the mains water supply. The value used here is an average of water rates across the EU.

Table 5
Performance data for 30 g TDS/L scenarios

Parameter	Scenario 1	Scenario 2
Flowrate (L/h)	1.2	1.2
Water recovery (%)	35.01	48
Permeate flow (m^3/d)	1.68	2.30
Brine flow (m^3/d)	3.12	2.50
Hydraulic power required (kW)	1.30	2.11
Electrical power supplied (kW)	1.13	2.76
Operation time (h/d)	4	4
Electrical energy (kWh/d)	4.52	8.50
Specific energy consumption (kWh/m^3)	2.69	3.69
System performance index	1.15	0.77

5. Discussion

5.1. Tannery LCCA

The NPV for the ERD system configuration (S1) was 15% higher than that of non-ERD configuration (S2) (Fig. 6). Brine disposal costs were 20% higher for S1 and accounted for 56.2% of the total LCC, and 52.9% of the LCC of S2. Because of the relatively small flowrate under consideration, the variation in CAPEX and replacements costs between configurations was significant. Replacements and CAPEX NPVs for S1 were 18% and 8.1% higher, respectively than S2. While the energy NPV for S1 was 46.8% lower than that of S2, the percentages of the total LCC attributed to energy were 1% and 2.1%, respectively, for S1 and S2. Similarly, the cost avoidance, or generated revenue from the production of water was minimal (–2.0% for S1, and –3.3% for S2 of the total LCCs). Sensitivity analysis indicates that there is no minimum brine disposal rate that could justify ERD implementation for the flowrate in question (Fig. 7).

5.2. Aquafarm LCCA

Variation in the aquafarm LCCs was much less than that of the tannery at just over 4%, with the ERD system (S3) configuration again being the higher of the two (Fig. 8). The percentages of the total LCCs attributed to brine disposal costs were even higher than that of the tannery (73.1% for S3 and 56.8% for S4), despite the lower brine production and higher water recovery rates. This is due in some part to the CAPEX and replacement cost scale economies associated with the higher flowrates. The percentage of the LCCs attributed to CAPEX for S3 and S4 were 24.3% and 23.73%, respectively. The capacity for brine recirculation resulted in a significant increase in the cost avoidance/generated revenue from water recovery (–14.8% for S3 and –16.8% for S4 of the total LCCs). The longer operational hours (24 and 20 h/d for S4 and S3, respectively), additional pumping for recirculation, and mixing for the aquafarm system configurations resulted in relatively higher daily energy consumption values than those of the at 5.8% and 9.1% of the total LCCs for S3 and S4, respectively. The increased significance

Table 6
Performance data for 5 g TDS/L scenarios

Parameter	Scenario 3	Scenario 4
Flowrate (m^3/h)	1.7	1.7
Water recovery per pass (%)	37	48
Water recovery total (%)	75	82
Total permeate flow (m^3/d)	15.04	16.32
Total brine flow (m^3/d)	4.96	3.68
Hydraulic power required (kW)	0.6–1.14	0.74–1.53
Electrical power supplied (kW)	0.97–1.33	0.99–2.02
Operation time (h/d)	24	20
Electrical energy (kWh/d)	30.08	34.73
Specific energy consumption (kWh/m^3)	2.0	2.13
System performance index	0.79	0.76

Table 7
Life cycle cost parameters and values, capital, and operation costs

Parameter	Value
System lifetime (years)	30
OPEX discount rate (%)	5
Energy discount rate (%)	12
Pump lifetime (y)	10
ERD lifetime (y)	10
Membrane lifetime (y)	3
Operation (d/y)	330
Specific costs	
Water (€/m^3)	0.4
Energy (€/kWh)	0.15
Brine disposal (€/m^3)	6
Capital costs (€)	
HPP	4,703
HPP + ERD	8,739
Membranes and pressure vessel (aquafarm)	3,250
Membranes and pressure vessel (tannery)	2,850
Fixtures	28,740
Automation and control	9,500
Feed pump	300
Recirculation pump	300

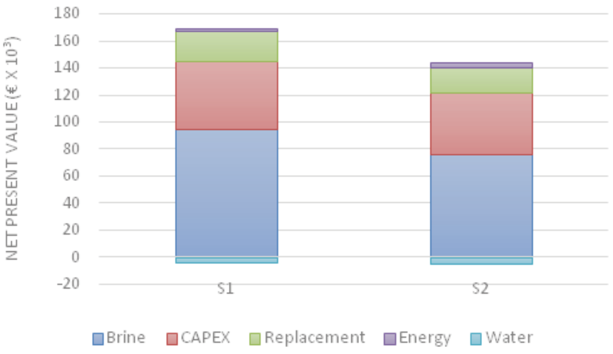

Fig. 6. Net present values of Scenarios 1 and 2.

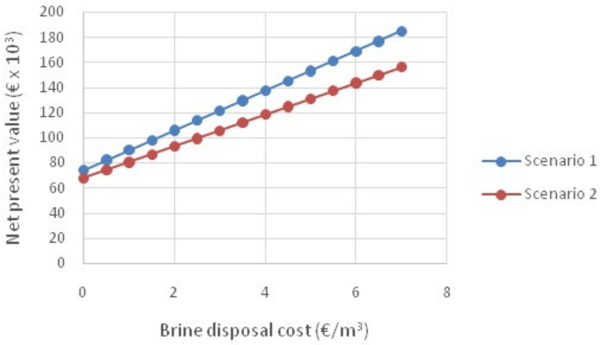

Fig. 7. Sensitivity of S1 and S2 NPVs with respect to brine disposal rate.

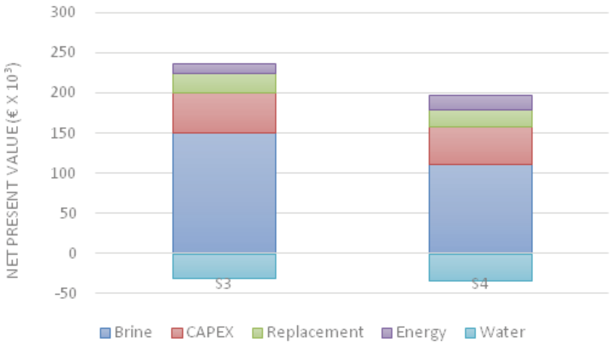

Fig. 8. Net present value of Scenarios 3 and 4.

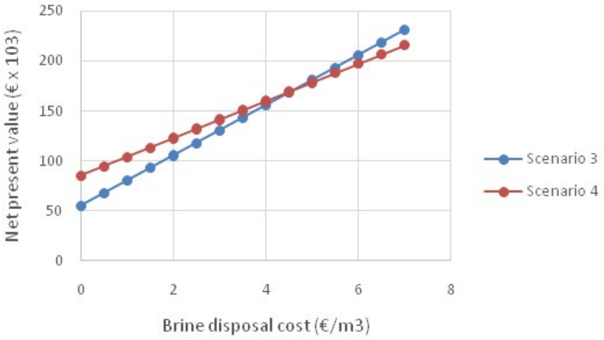

Fig. 9. Sensitivity of S3 and S4 NPVs with respect to brine disposal cost.

of energy consumption in these scenarios increases the value of an ERD. At brine disposal rates of below €4.59/m^3 ERD implementation becomes economically viable (Fig. 9).

6. Conclusion

Food and beverage companies that are obliged to desalinate, whether for the purpose of water reuse or simply to comply with discharge limits face significant economic burdens, and in particular for those companies producing small WW flows. The primary LCC elements of the desalination system are the CAPEX, replacement of membranes and pumps, brine disposal, and energy consumption. The implementation of an ERD provides the potential to reduce the percentage of the LCCs attributed to energy consumption; however, this creates a trade-off between energy, water recovery, and brine production. Brine disposal was found to represent the largest percentage of the total LCCs in all of the examined scenarios. At very small flowrates (<5 m^3/d) the additional cost of the ERD alone, and subsequent replacements, is enough to negate any economic gains achieved through the recovery of energy, regardless of the cost of brine disposal. However, that is not to say that there would not be environmental gains that could be achieved. At higher flowrates (>20 m^3/d) it was evident that energy recovery became more significant. It is, therefore, reasonable to assume that ERD implementation would be feasible at flowrates approaching 40–50 m^3/d. However, the variation in salinity needs to be considered in the context of this study. The capacity to recirculate the initially low concentration brine meant that the system operated for longer during the day and therefore could take advantage of the energy recovery, but at a much lower ERD efficiency. This aspect of the analysis is worthy of further investigation.

The large investment and operational costs for desalination of the small volume of the tannery final effluent poses a broader question on the economic feasibility of the system, in that it may be more economical to have the final effluent removed by an external contractor. However, such an assessment would require extending the boundaries of the analysis to include all of the wastewater treatment costs prior to entry to the RO system, which is beyond the scope of the current study.

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