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Energy consumption of reverse osmosis seawater desalination – possibilities for its optimisation in design and operation of SWRO plants

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ABSTRACT

Seawater desalination with reverse osmosis has taken a noteworthy upturn in recent years. One of the reasons for the success of the membrane process is its lower energy consumption in comparison to the thermal desalination processes. Due to advances in the efficiency of energy recovery systems of the seawater desalination stage (1st Pass) of SWRO – plants in the last decade this advantage of membrane processes has even increased.

Now, however, the energy consumption of an SWRO is also influenced by a huge number of additional factors. These are of an external nature as well as determined by design and configuration of the plant. Environmental conditions and – stipulations dependent on the location of the plant and furthermore the influence of operating modes are additional factors.

The individual systems of an SWRO plant – in particular its pre-treatment stage as well as its first and second passes are very closely cross-linked systems in regard to its energy consumption. During energy optimisation in design and operation of an SWRO besides the choice of the manner of the energy recovery in the 1st pass special attention must also be directed to the pre-treatment process and the interaction of these systems.

Ways to optimize design and operation of a seawater reverse osmosis plant under the aspect of lowering its energy consumption are investigated. After listing the basic design parameters for SWRO engineering, additional system design features and configuration aspects for of pre-treatment and RO systems influencing its energy consumption are identified and their degree of influence discussed. With a technical design framework optimized for low energy consumption an exemplary SWRO system of commercially size is developed. This plant is investigated concerning the range of its specific energy consumption at different seawater feed conditions. Then additional options for energy saving during operation of the SWRO are examined. Finally it is shown, what cost saving potential is generated by a certain range of energy saving margins under plant lifecycle aspects.

For plant design and determination of the specific energy consumption of the SWRO, an SWRO plant calculation and design model was used, which covers different pre-treatment and RO configurations and the design and energy consumption of the SWRO plant systems including potabilisation and subsystems like additional wastewater treatment and sludge dewatering facilities of an SWRO.

A characteristic SWRO plant size (20,000 m^3/d net output capacity) and configuration (two pass RO system) was selected for modelling purposes.

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With the most efficient energy recovery system, the work exchanger specific energy consumption under the modelling conditions for the 1st + 2nd RO parts of the SWRO plant is in between of about 3.6 to nearly 4.0 kWh/m^3. The Turbocharger energy consumption is about 0.5 kWh/m^3 higher, such of Pelton turbine about 0.7–0.8 kWh/m^3 more. The overall consumption of an SWRO plant of this system configuration with various types and efficiencies of pre-treatment, a two pass RO part and treatment of process wastewater and sludge dewatering adds up to between 3.9 and 5.6 kWh/m^3, depending on feed temperature and type of pre-treatment and energy recovery systems.

Considering the various aspects to be taken into account for optimization of energy consumption in seawater reverse osmosis plants and the fact, that in most cases these measures are offset by increases in capital costs for equipment or possibly also in chemical consumption, optimisation of the energy consumption of SWRO plants during planning and operation is a quite extensive and complicated matter and a demanding engineering task.

1. Introduction

Seawater desalination with reverse osmosis has taken a noteworthy upturn in recent years.

One of the reasons for the success of the membrane process is its lower energy consumption in comparison to the thermal desalination processes.

The high-pressure RO desalination stage is undoubtedly the dominating energy consumer of a SWRO. Under the aspect of the rapidly increasing energy costs and intensified environmental awareness it is understandable that greater attention is directed in particular to this section of a membrane desalination plant and energy optimisation there. Energy consumption of a SWRO however is also influenced by a huge number of additional factors. These are as well of external nature, as also determined by design and configuration of the plant. Also environmental conditions and – stipulations dependent on the location of the plant as well as furthermore the influence of operating modes are being added.

Basic design parameters for an SWRO plant are

- Net production capacity of product water
- Composition of permeate and product water produced from it (salinity, constituents like boron, bromide, alkalinity etc.)
- Sea water salinity and its variation over the year
- Sea water temperature and its variation over the year
- Permeate recovery of the reverse osmosis possible under these conditions
- Impurities of sea water to be removed by suitable pre-treatment measures.

From these basic parameters secondary design targets are derived for the individual components of the SWRO plant. This applies in particular to the membrane design and the configuration of the reverse osmosis system, but also to the pre-treatment part. Such design parameters and configuration options are:

- Selection of a pre-treatment system, customized for the site conditions of the SWRO
- Membrane type for 1st and 2nd pass
- Optimized recovery rates in 1st and 2nd pass
- Optimized design parameters and membrane configuration for RO like
    - Average flux and stand- by train
    - Fouling factor and flux decline assumption
    - Membrane replacement and average membrane life selection
    - Number of elements per vessel
    - RO train configuration (centre or train oriented)
    - RO train size for highest efficiency of feed pumps
    - Split partial application and its influence on 2nd pass capacity
    - p_H conditions in feed to 1st and 2nd pass
    - Minimization of all RO feed conditions which reduce efficiency of energy recovery

2. Pre-treatment, process configurations and their share in energy consumption of an SWRO plant

Table 1 shows possible pre-treatment processes and their configurations that must be applied depending on the quality of the sea water to be processed. The table also lists values of the specific energy consumption SEC_{PRF} based on the processed filtrate for the different pre-treatment processes.

This shows that floc filtration with gravity filters and with the use of a static mixer is clearly the most energy friendly pre-treatment process for both single- and two-stage filtration. Membrane filtration could be at a comparable level to floc filtration with floc basins followed by more extensive conventional pre-treatment processes.

For determination of the share of the pre-treatment in the overall energy demand of the desalination

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Table 1
Specific energy consumption of pre-treatment configurations (based on pre-treated water)

No.	Type of pre-treatment process	No. of filtration stages	Abbreviation	SECPRF kWh/m^3
1	Floc gravity filtration + static mixer	1	FF + SM – 1F	0.015
		2	FF + SM – 2F	0.02
2	Floc gravity filtration + floc basins	1	FF + FB – 1F	0.10
		2	FF + FB – 2F	0.12
3	Sedimentation + Filtration	1	S + F – 1F	0.14
		2	S + F – 2F	0.15
4	Flotation + filtration	1	DAF + F – 1F	0.15
		2	DAF + F – 2F	0.16
9	Membrane filtration	–	MF	0.1–0.2
10	Flotation + membrane filtration	–	DAF + MF	0.25

process its specific power demand must be based on the product output of the whole SWRO plant. This parameter $\mathrm{SEC_{PRP}}$ is calculated from the specific power demand $\mathrm{SEC_{PRF}}$, referring to treated filtrate as shown in Eq. (1).

$$\mathrm{SEC_{PRP}} = \frac{\mathrm{SEC_{PRF}}}{Y_T} \tag{1}$$

$\mathrm{SEC_{PRP}}$ = Specific energy consumption pre-treatment process based on net plant output capacity
$\mathrm{SEC_{PRF}}$ = Specific energy consumption pre-treatment process based on treated feed capacity
Y_T = Recovery rate factor SWRO total

$$Y_\mathrm{T} = \frac{Y_1}{\left[(1 - R_{C2}) + \frac{R_{C2}}{Y_2}\right]} \tag{2}$$

$$R_{C2} = \frac{Q_{O2}}{Q_{\mathrm{OG}}} \tag{3}$$

$$R_{C2} = \frac{c_B - c_M}{c_B - c_{P2}} \tag{4}$$

Y_1 = Recovery rate factor 1st pass
Y_2 = Recovery rate factor 2nd pass
R_{C2} = Capacity factor 2nd pass
Q_{OG} = Plant gross production capacity [m^3/h; m^3/d]
Q_{O2} = Production Capacity 2nd pass [m^3/h; m^3/d]
c_B = Concentration in bypass from 1st pass (permeate or split partial product)
c_M = Target concentration in mixed product
C_{P2} = Concentration in permeate 2nd pass

The value of the overall permeate recovery or the permeate recovery factor Y_T, as shown in Eq. (1) is dependent on the yield of the first pass Y_1, the 2nd pass Y_2 and the capacity factor of the 2nd pass R_{C2} Eq. (2). The capacity factor of the 2nd pass is to be understood as the ratio of the capacity of the 2nd pass to the overall production capacity of the SWRO Eq. (3). R_{C2} again is calculated according to Eq. (4) from the concentration conditions of the permeate from the 2nd pass and the bypass flow from 1st pass around the post desalination stage as well as the target value for the corresponding lead substance in the final product (see Fig. 1).

Permeate constituents, which are the determining factor for the capacity needed for the 2nd pass are, according to the target values for the composition of the drinking water are boron, the total dissolved solids (TDS) content or also the bromide concentration.

The lower the concentration of these constituents is in the permeate of the first pass, the lower the capacity of the 2nd pass need be. Here the advantage of the split-partial configuration of the first pass becomes apparent. The quality of front permeate extracted from the first elements of the first pass is noticeably better than that of permeate produced as a mixture of all elements of a membrane pressure vessel. (see Fig. 2).

The lower the values of Y_1 and Y_2 are and the greater R_{C2} is, the more seawater is to be fed to the SWRO plant and the more power is consumed in pre-treatment.

Fig. 3 shows the interdependency between overall permeate recovery Y_T and the abovementioned design and operating parameters of the reverse osmosis section of the plant. Depending on seawater salinity and temperature a permeate recovery of 50% up to 55% at favourable conditions is possible in the RO 1st pass. This largely depends on the flow pattern as well as the acceptable permeate recovery for the individual membrane elements in their assembly in the membrane pressure vessels as predefined by the membrane manufacturers.

The graph in Fig. 3 shows, that these RO design and operation parameters can influence the overall product

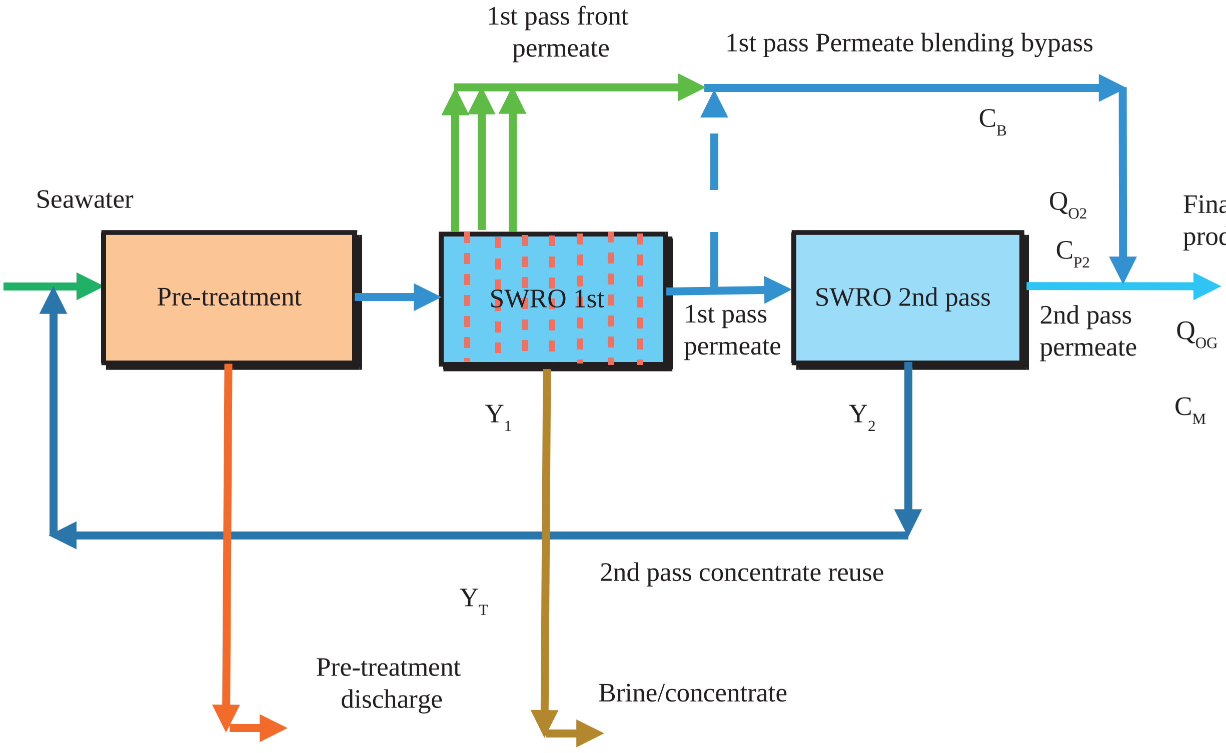

Fig. 1. RO Two Pass Configuration with Split Partial Extraction in 1st pass.

recovery rate of the SWRO in an order of magnitude of up to 4–5 percentage points. In the most favourable case i.e. $Y_1 = 0.5$, $Y_2 = 0.9$ and the 2nd pass of the RO operated only with 50% of the plant's output ($R_{C2} = 0.5$) a maximum overall recovery rate of the SWRO of approx. 47%, and in the least favourable case ($Y_1 = 50\%$, $Y_2 = 85\%$, $R_{C2} = 1$) approx. 43% is possibly.

The graph Fig. 4 shows the influence of the overall plant recovery rate Y_T on the specific energy consumption of the pre-treatment stage, referred to as the product output of the plant. This value ranges from 0.05 to 0.8 kWh/m^3. Of course, the flotation – microfiltration configuration with a SEC$_{PRP}$ of 0.8 is to be understood as ''a worst case scenario'' i.e. this energy consumption is only to be considered if highly polluted sea water has to be brought up to a suitable quality for the RO membranes in pre-treatment stage.

3. Reverse osmosis – core of the SWRO and its energy consumption

3.1. Permeate recovery rate and energy consumption optimum

The power demand of the reverse osmosis section of an SWRO plant depends greatly on the respective product recovery rate in the RO's 1st and 2nd pass.

As permeate recovery increases also the cycles of concentration and with these the salinity in the membrane elements of the RO rise. Accordingly, the operating pressure needed for the reverse osmosis will increase. However, the permeate quality also deteriorates, so a higher capacity is needed for the 2nd pass. But in parallel the feed flow to the SWRO plant goes down and with it also the power demand for pre-treatment.

Energy recovery systems utilized in large-scale technical desalination plants are

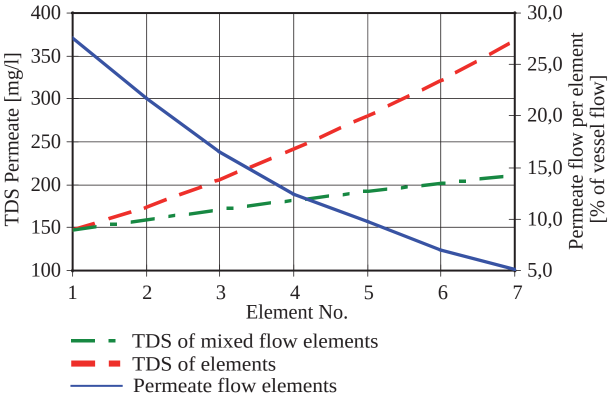

Fig. 2. Permeate quality of individual membrane elements and in split – partial extraction.

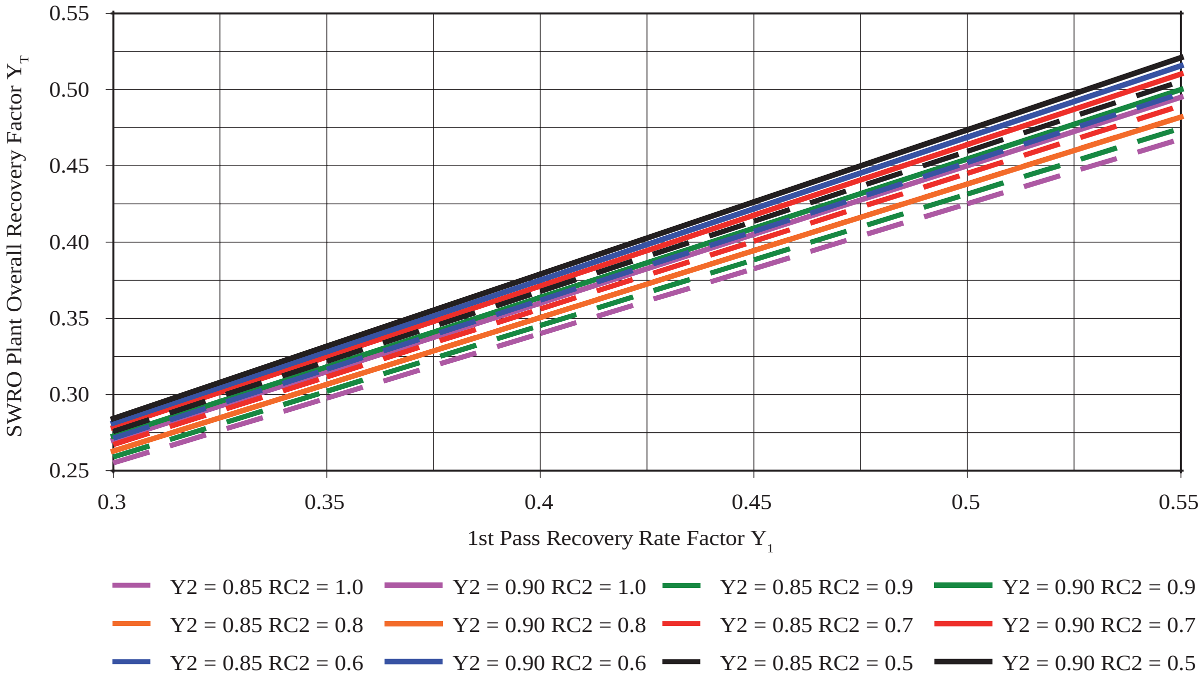

Fig. 3. Dependency of SWRO overall recovery rate on 1st pass and 2nd pass recovery rate and 2nd pass capacity ratio.

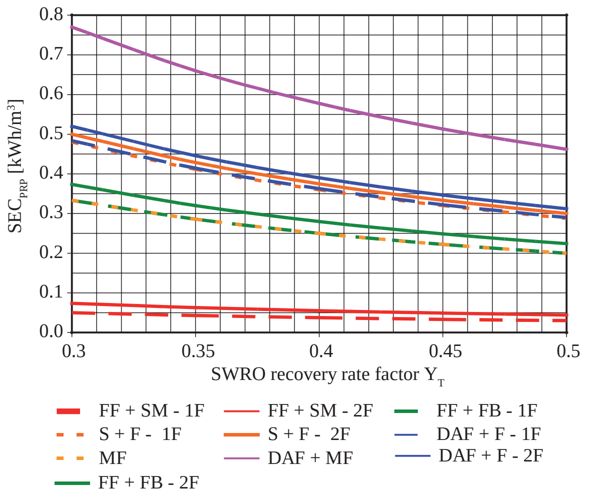

Fig. 4. SEC_{PRP} of different pre-treatment processes vs. SWRO recovery rate.

- Pelton turbine
- Isobaric systems (work and pressure exchanger)
- Turbocharger

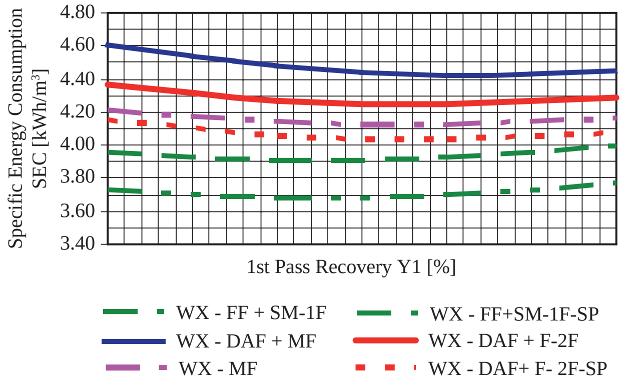

Fig. 5. Work exchanger – SEC of pre-treatment + RO versus 1st pass recovery [20% split partial = SP and 100% 2nd pass capacity].

The graph in Fig. 5 for the work exchanger as energy recovery system illustrates the variation of the specific power demand of the plant as a function of permeate recovery in the RO first pass. In addition, different curves are shown there for some kinds of pre-treatment as well as for operation of the 2nd pass with 20% split partial = 80% capacity and full 100% capacity. Split partial operation in this case reduces energy consumption of the RO process by about 0.2 kWh/m^3.

For a pre-treatment process with lower energy consumption (floc filtration with inline mixer) the minimum energy consumption is at about $Y_1 = 41$–42%. For more energy-intensive pre-treatment systems the minimum of the specific energy consumption shifts more in the direction of $Y_1 = 44$–45%. While the energy course of the work exchanger shows a distinctive minimum, this is not the case with the other energy recovery systems at least not in the range of the permeate recovery up to 50% as is feasible in the 1st pass (Fig. 6).

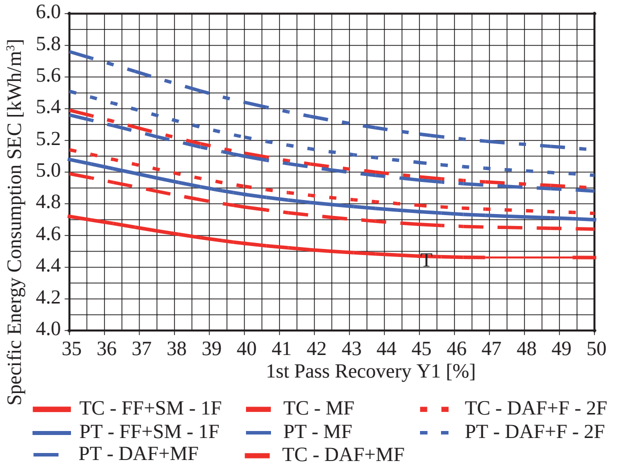

Fig. 6. Turbocharger and pelton turbine – SEC of pre-treatment + RO versus 1st pass recovery [100% 2nd pass capacity].

The specific energy consumption for the Turbocharger (TC) as well as for the Pelton turbine(PT) decreases at a greater rate at the beginning, but then this flattens out to a more-or-less constant level at $Y_1 = 45$–46 percent.

3.2. *Membrane feed and RO operation pressure and average membrane lifetime (AMLT)*

In membrane design the feed pressure P_{FM} to the membranes or the necessary driving pressure P_D to achieve the necessary product output are important parameters. The detailed design of the pump groups and the energy recovery systems in the 1st pass is based on these values.

The equations below (Eqs. (5) and (6) show, how the operating pressure P_{OP} for the 1st and 2nd pass as the design basis for the design of the RO system and the calculation of the power demand is made up of driving pressure P_D, membrane feed pressure P_{FM} and the sum of the pressure losses of the respective RO feed systems and additional pressure losses between stages:

$$p_{OP} = p_{FM} + \sum \Delta p_F \tag{5}$$

$$\sum \Delta p_F = \Delta p_{PV} + \Delta p_P + \Delta p_V + \Delta p_T + \Delta p_F + \Delta p_{CF} + \Delta p_{Ist} + \Delta p_{SH} \tag{6}$$

p_{OP} = Operating pressure RO [bar]
$\sum \Delta p_F$ = Sum of RO feed systems pressure losses [bar]
Δp_{PV} = Pressure loss membrane pressure vessels [bar]
Δp_P = Pressure loss feed piping [bar]
Δp_V = Pressure loss feed valves [bar]
Δp_T = Pressure loss due to throttling [bar]
Δp_F = Fouling margin pressure differential [bar]
Δp_{CF} = Pressure loss cartridge filter [bar]
Δp_{Ist} = Interstage piping pressure losses (2nd pass only) [bar]
Δp_{SH} = Static head pressure differential [bar]

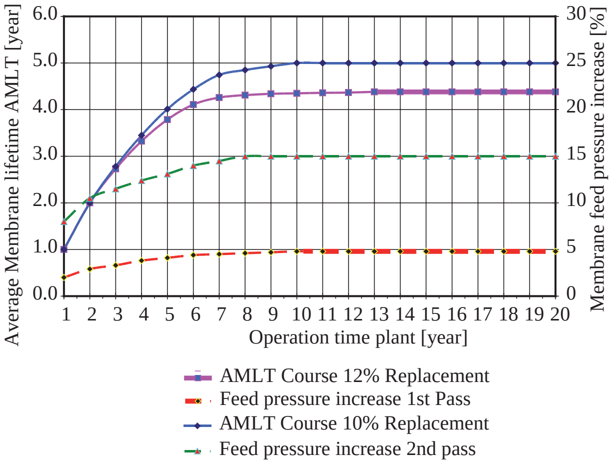

Fig. 7. Course of AMLT vs. membrane replacement rate and operation pressure increase with AMLT.

The energy to be applied to compensate for the pressure loss $\sum\Delta\, p_F$ and of the pressure drop in the membrane elements Δp_E is lost and cannot be recovered in the energy recovery device.

In an RO plant, where elements with different lifetime are available the resulting average membrane lifetime $AMLT_{P,\,T}$ is defined by following Eq. (7):

$$AMLT_{P,T} = \frac{\sum MLT_E}{n_E} \tag{7}$$

$AMLT_{P,T}$ = Average membrane lifetime of membranes in plant/train [years]
MLT_E = Membrane lifetime of single membrane element [years]
n_E = number of elements in plant/train

Thus average membrane lifetime is also dependent on the replacement rate of the membranes or the membrane replacement strategy, that operation of the RO system is based on. The graph of Fig. 7 shows, how the average membrane lifetime AMLT of an RO plant varies with differing replacement rates – 10% and 12%- of the membranes.

From commissioning of the plant onwards, the age of its first membranes installed increases. If membranes are replaced simultaneously, then after a certain operating time an average membrane age will be reached, at which all initially installed membranes

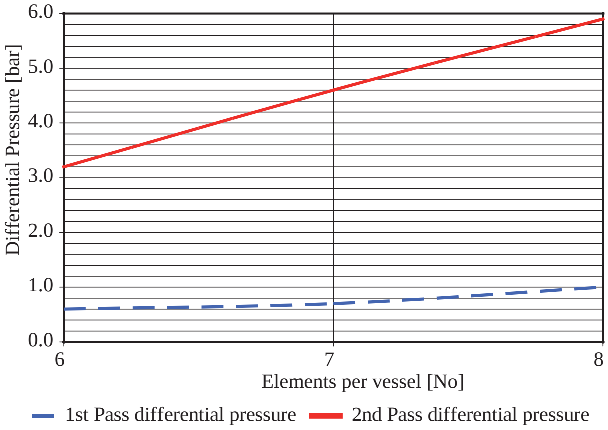

Fig. 8. Dependency of pressure loss due to element number on number of elements per vessel in 1st and 2nd pass.

will have been replaced. For an average membrane replacement rate of 12% this will be the case after an operation time of approx. 8 years, for 10% after approx. 10 years.

In step with the average membrane age of the plant going up, the flux rate through the membranes decreases. To maintain the plant output, the operating pressure must be raised accordingly. At the same time it fluctuates depending on the variations of temperature and salinity of the sea water and from cleaning to cleaning.

3.3. Membrane element configuration of the pressure vessels

The membrane feed pressure P_{FM} is an output value of the design programs of the membrane manufacturers [3], [4], [5]. This pressure also includes the pressure loss of the membrane elements depending on the number of elements per membrane pressure vessel selected for design.

The graph in Fig. 8 shows the dependency of the pressure loss on the membrane elements in the 1st pass and a three-staged 2nd pass of an RO on the number of elements per pressure vessel.

In the 1st pass the pressure loss rises with increasing number of elements from 6 to 8 moderately by around approx. 0.4 bar. However, pressure loss increase is much more pronounced in the 2nd pass with from 2 to 3 concentrate stages and differential pressure goes up by nearly 3 bar.

3.4. Average specific membrane flux

For seawater desalination with surface water extraction the bandwidth of the average membrane flux is quoted by membrane manufacturers as being in the range of 11–17 l/m^2, h. Even up to 20 l/m^2, h may be considered for membrane filtration as pre-treatment. Fig. 9 shows the rise of membrane feed pressure for a seawater desalination membrane over the range of just 12–15 l/m^2, h of average membrane flux. Nevertheless, at the same time also permeate quality improves with a positive effect on the capacity needed for the 2nd pass. So this design parameter too must be considered for energy optimisation of the RO section of the SWRO plant.

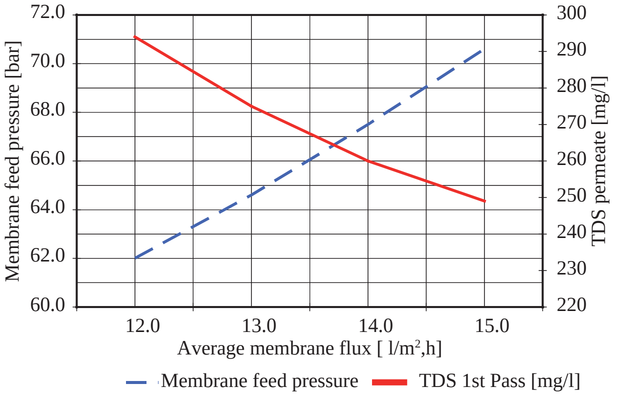

Fig. 9. Membrane feed pressure and permeate TDS vs. average membrane flux.

3.5. RO – system design and system configuration

The selection of the energy recovery system for the reverse osmosis process is the deciding factor for the base level of the energy consumption of a SWRO.

The energy recovery systems used in large-scale technical desalination plants

- Pelton turbine
- Isobaric systems (work and pressure exchanger)
- Turbocharger

differ noticeably in their energy recovery efficiency.

However, not only the type of energy recovery system in the RO core process determines the SWRO energy consumption.

Further possibilities exist in train configuration and in the equipment part of the RO – section.

Here specifically

- Optimization of train configuration, as this is possible according to the choice of the energy recovery system. With an isobaric system, this implies the choice between purely train oriented and a more or less centralised RO feed and energy recovery configuration.
- Design optimization of the reverse osmosis-pump group concerning pump size and efficiency.

Table 2
RO configuration options

Option	Option characteristics
1	Feed centre configuration 2 or 3 membrane units per RO feed pump group in a pumping centre with an ERD assigned to each of the units.
2	Three centre configuration RO 1st pass consisting of pumping, membrane and energy recovery centre, where the RO trains are fed from a pumping centre equipped with a lower number of feed pumps, than the number of RO trains installed in the membrane centre via a common feed header. Concentrate from the membrane centre is collected in a common concentrate ring and fed to the isobaric ERD energy recovery centre. The pressurised seawater feed part stream from there is supplied to the common feed ring of the pumping centre via ERD booster pumps.
3	Train configuration RO 1st pass consisting of a certain number of trains, each with its own seawater feed pump group, membrane unit and ERD, assigned to each train.

3.6. Train configuration and stand-by trains

If an isobaric energy recovery device (ERD) is used, there are basically three options for train configuration (Table 2):

Pump efficiency improves with larger feed pump size especially for high-pressure pumps. However dependent on type and make of pumps this efficiency improvement no longer applies above a certain maximum capacity of the pumps and with a certain efficiency level, which can not be improved on. Such a maximum efficiency level is attained at about 86–88% at flow rates specific for pump type and design [1,2]. For the Pelton turbine and Turbocharger this optimum size of the HP pumps is reached earlier for a certain plant size, as the full unit feed flow must be pumped. With isobaric systems feed flow is of the order of the permeate flow of an RO unit. Pump sizes with optimised efficiency for isobaric systems can be attained by combining a number of smaller RO units to be fed by one RO feed pump group as in the centre mode or by increasing the size of the units to be fed by one pump group in a train design.

Options 1 and 2 need special flow control systems for appropriate and well balanced flow from the common pump and EDS headers to the trains. The additional hydraulic control facilities in such feed or three-centre design give rise to pressure losses that must be considered in the overall systems energy efficiency and also for a comparison with train design.

In a feed centre or three-centre design the feed centre must feed seawater to the membrane units under the conditions determined by the unit with lowest performance. From experience the hydraulic conditions of the trains will not be the same. So if appropriate capacity can only be attained from certain membrane units/trains under increased feed pressure, the feed centre has to provide these conditions. Feed to units, that are to be operated at less pressure, must be throttled even if variable speed drives are fitted to the feed booster or high-pressure pumps of the feed centre.

With train oriented configuration, each train can be operated at its individual necessary feed conditions without affecting or being affected by other trains.

Stand-by trains improve the availability of the RO and prevent specific operating conditions for example by adapting average flux to feed conditions of the RO or during outage of one train for cleaning or membrane replacement. Also the plants gross capacity to compensate for outage losses can be reduced. Both aspects are positive for energy consumption of the plant.

4. SWRO reference plant design and specific power demand modelling

4.1. Energy consuming systems of a SWRO

The structure of a typical SWRO plant for the production of drinking water is shown in Fig. 10 in simplified form.

The energy consumption in total of the desalination plant EC_{total} consists of the power consumption of the individual process systems and treatment stages of the SWRO and its infrastructure (auxiliary systems, air conditioning, lighting, communication systems etc.) as well as workshops, warehouses, laboratory and administrative building. (see Fig. 10, Eq. (8))

$$\begin{aligned} EC_{\text{total}} &= EC_{\text{SEP}} + EC_{\text{Pr}} + EC_{\text{RO}} + EC_{\text{Pot}} + EC_{\text{WWT}} \\ &\quad + EC_{\text{Pi}} + EC_{\text{Aux}} + EC_{\text{Inf}} + EC_{\text{Dwp}} \end{aligned} \tag{8}$$

EC_{total} = Energy consumption (EC) total of SWRO plant
EC_{SEP} = EC seawater extraction, screening and pumping systems
EC_{Pr} = EC pre-treatment system
EC_{RO} = EC reverse osmosis system with 1st and 2nd pass demand and cleaning
EC_{Pot} = EC potabilisation
EC_{WWT} = EC wastewater treatment and sludge dewatering

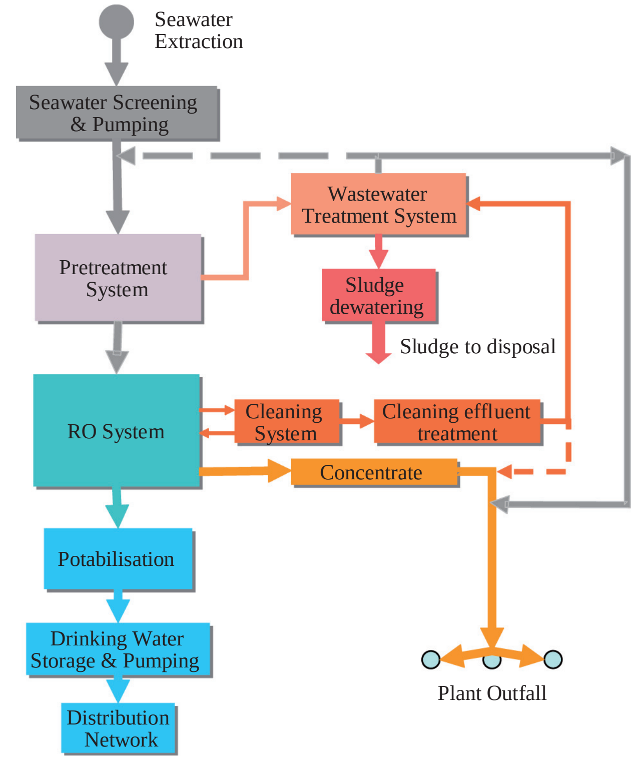

Fig. 10. Typical plant configuration of SWRO plant.

EC_{Pi} = EC internal pumping necessary due to specifics in hydraulic profile of plant
EC_{Aux} = EC auxiliaries (process air and water, process HVAC. etc.)
EC_{Inf} = EC of administration buildings, workshops and storage, laboratories, non process HVAC, communication systems, lighting etc.)
EC_{Dwp} = EC drinking water pumping to supply network

4.2. SWRO plant design and modelling

With a SWRO plant model, which covers the different pre-treatment and RO configurations and also provides design and energy consumption of potabilisation and additional wastewater treatment and sludge dewatering facilities the specific energy consumption of an SWRO plant and its subsystems was determined.

A characteristic SWRO plant size and configuration was selected for modelling.

Table 3 shows the basic design parameters for this plant:

Table 3
SWRO basic design data

Parameter	Unit	Value/Value range
Plant capacity		
Net output capacity	m^3/d	200,000
Availability ratio	%	95
Net production capacity	m^3/d	210,526
Gross production capacity	m^3/d	212,000
Seawater conditions		
Total dissolved solids	mg/l	40,000
Temperature	°C	15–30
Suspended solids	mg/l	2–10
Boron	mg/l	5.7
Drinking water quality		
Total dissolved solids	mg/l	200
Alkalinity	mmol/l	1.0
	ppm $CaCO_3$	50
Boron	mg/l	1.0

As net – plant output of the SWRO plant 200,000 m^3/day was chosen, a plant capacity which at the moment is in the upper range of the SWRO technology, but is no longer uncommon. For plant availability a 95% of annual average is taken as the basis. From this, and the net – plant output, net and gross production capacities are calculated as follows (Eqs. (9) and (10)):

$$Q_{ON} = \frac{Q_N * 100}{R_{Av}} \tag{9}$$

$$Q_{OG} = Q_{ON} + Q_{id} \tag{10}$$

Q_N = Plant net output capacity [m^3/d]
Q_{ON} = Plant net production capacity [m^3/d]
Q_{OG} = Plant gross production capacity [m^3/d]
Q_{id} = Internal process water demand capacity of plant [m^3/d]
R_{Av} = Availability ratio [%]

In the following Table 4 selections of design values are listed, which were chosen based on the energy consumption consideration as described above.

The configuration of the RO is chosen as train wise, each with its own HP and ERD pump group and ERD device. The same train concept also applies for the feed pumps of 2nd pass.

The 1st pass is operated in split-partial configuration of its membrane stage. For the 2nd pass a capacity of 80% of the plant gross production capacity was taken as the basis for modelling. This value is an average value based on operation, when the 4.5 year design AMLT is reached.

Table 4
Input parameter for RO membrane design

Parameter	Unit	Selected value/range
1st pass		
Recovery	%	45
Average membrane flux	l/m^2,h	13.5
Flux decline rate	%/ year MLT	7
Design AMLT	year	4.5
Average membrane replacement rate	%	12
Number of elements /vessel	No	7
Permeate backpressure	bar	0.5
Concentrate /wastewater discharge pressure	bar	1.5
Cleaning-in-place	No/year	2
2nd pass		
Recovery	%	90
R_{C2} 2nd pass	%	80
Average membrane flux	l/m^2,h	35.5
Flux decline rate	%/year MLT	5
Design AMLT	year	5.0
Average membrane replacement rate	%	10
Number of elements/vessel	No	6
Permeate backpressure	bar	0.5
Cleaning-in-place	No/year	1

For the isobaric energy recovery system a mixing rate such of a pressure exchanger system was chosen.

As potabilisation process, treatment with lime hydrate/CO_2 is used.

Wastewater from the pre-treatment stage of the SWRO is processed in a waste water treatment plant (WWTP) and the sludge of the WWTP dewatered for appropriate disposal.

In Table 5 efficiencies are listed for the most important pumps and drives of the SWRO as well as of the Pelton turbine and Turbocharger of the energy recovery systems. Also the input values for the plant modelling are shown in this table. The listed efficiencies of the pumps are based on operation and guarantee values of pump suppliers from current projects and from plants in operation.

For plant equipment, that is not continuously operated, their energy consumptions are calculated on basis of average annual operation time. During implementation of such sequential activities (cleaning, flushing, etc.) the SEC of the plant will be noticeably higher than the values for SEC shown in the following tables.

The specific energy consumption of the whole plant EC_{total} is calculated from the sum of the energy consumption of the individual systems and net-production capacity Q_N as follows Eq. (11)

$$SEC_P = \frac{EC_{total} * 24}{Q_N} \tag{11}$$

SEC_P = Specific energy consumption plant [kWh/m^3]
Q_N = Plant net output capacity [m^3/d]

The SEC values quoted in Table 6 apply of course only for the basic design conditions and design parameter as listed in Tables 3–5.

SECs for seawater TDSs other than the TDS basis of 40,000 mg/l and the seawater temperature range of this model are quoted and discussed elsewhere [6]

With the most efficient ERS, the specific energy consumption with work exchanger at the conditions of the model for the RO 1st + 2nd part of the SWRO is from about 3.6 to nearly 4.0 kWh/m^3. The energy consumption with Turbocharger is about 0.5 kWh/m^3 higher, with that of the Pelton turbine about 0.7–0.8 kWh/m^3 more. The overall consumption of an SWRO of this system configuration with different types and efficiencies of pre-treatment, a two- pass RO section and treatment of process wastewater and sludge dewatering adds up to between 3.9 and 5.6 kWh/m^3, depending on feed temperature and type of pre-treatment (Fig. 11).

Fig. 11 shows that appropriate selection of the pre-treatment process is of real importance for the optimizing SWRO energy consumption. Pre-treatment SEC can go to higher than 10% of the overall plant SEC. So this process must be customized for the seawater quality conditions at the plant site. Selection of a system with too much of a safety margin in performance and efficiency would lead to unnecessarily high SEC values. However, a process configuration, which is inadequate for handling the whole range of seawater quality fluctuations at the plant site would give rise to increases operating cost or in case of retrofitting of the SWRO also additional CAPEX during the lifetime of the plant.

5. Possibilities for energy optimization during SWRO operation

An energy-optimised design should include degrees of freedom that allow influence to be exerted on energy consumption and its minimisation during plant operation. The factors to be considered for the design of the RO part to allow this are specifically:

- Possibility of matching the capacity of the 2nd pass to be possible to the permeate quality of the 1st pass and its feed quality
- Flexibility in train capacity, which over a certain range should allow the average flux of the membranes to be

Table 5
Efficiencies of Pumps, energy recovery devices and motor drives

Type of pumps/ERD	Unit	Efficiency – state-of-art range	Selected value/range	Notes
Pumps				
RO 1st pass				
HP feed booster pump	%	82–85	84	
HP pump	%	85–88	87	Depending on pump size
ERD feed booster pump	%	82–85	84	
ERD booster pump	%	82–84	83	
Permeate intermediate pumps	%	82–85	83	
RO 2nd pass				
2nd pass feed pumps	%	84–86	85	
Permeate pumps	%	82–85	83	
ERD				
Pelton turbine	%	86–88.5	88	
Turbocharger	%	75–83	80	Depending on capacity
Motor drives				
Motor & Drive	%	94–96	95	

Table 6
Specific energy consumption of an SWRO plant for different energy recovery systems for a seawater TDS of 40,000 mg/l, feed temperature range of 15–30 °C and various pre-treatment configurations

Type of Pre-treatment	*t*	SEC_{Plant}			$SEC_{RO\ 1\&2}$					
		Work exchanger	Turbo-charger	Pelton	Work exchanger	Turbo-charger	Pelton	SEC_{PR}	SEC_{POT}	SEC_{WWT}
	°C	kWh/m^3	kWh/m^3	kWh/m^3	kWh/m^3	kWh/m^3	kWh/m^3	kWh/m^3	kWh/m^3	kWh/m^3
FF + SM – 1F	15	4.14	4.66	4.94	3.92	4.43	4.70	0.036		0.019
	20	4.01	4.51	4.78	3.79	4.28	4.55	0.035		0.019
	25	3.91	4.39	4.66	3.69	4.17	4.43	0.034		0.019
	30	3.84	4.32	4.59	3.62	4.09	4.36	0.033		0.019
MF	15	4.38	4.90	5.18	3.94	4.45	4.73	0.221		0.042
	20	4.24	4.76	5.03	3.81	4.31	4.58	0.215		0.042
	25	4.13	4.63	4.90	3.71	4.20	4.47	0.210		0.042
	30	4.06	4.54	4.81	3.64	4.12	4.38	0.205		0.041
DAF + F – 2F	15	4.52	5.05	5.33	3.93	4.44	4.72	0.396	0.005	0.025
	20	4.37	4.85	5.13	3.78	4.26	4.53	0.395		0.024
	25	4.29	4.79	5.06	3.70	4.19	4.46	0.394		0.024
	30	4.22	4.70	4.97	3.63	4.11	4.37	0.394		0.024
DAF + MF	15	4.78	5.31	5.59	3.96	4.48	4.76	0.588		0.052
	20	4.64	5.15	5.43	3.83	4.33	4.61	0.580		0.052
	25	4.47	4.97	5.24	3.74	4.23	4.49	0.508		0.052
	30	4.37	4.86	5.13	3.66	4.14	4.41	0.484		0.052

influenced and thus also permeate quality and membrane feed pressure (see Fig. 9). This is achieved specifically by equipping the plant with stand-by trains.

- Possibility of applying increased dynamic permeate back-pressure (permeate throttling)

The interplay of adaptation of average flux and permeate back-pressure can contribute substantially to power-saving operation of the high-pressure pump group of the RO. It must be considered, that the operating pressure of the 1st pass must be varied in a rather extensive bandwidth between the best operating conditions at plant commissioning (new membranes, low fouling etc.) and worst conditions during the lifetime of the RO at minimum temperature and with older and fouled membranes. For the

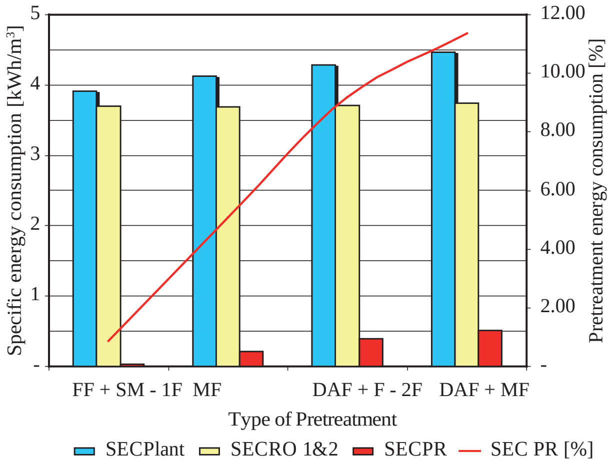

Fig.11. Specific energy consumption of SWRO and pretreatment process stages.

reference-plant this operating pressure range may be as much as to 8 bar or even more. Even higher values arise for the 2nd pass.

Even if the operating pressure split with a duplicate – pump group (high-pressure pump and booster-pump in the 1st pass) and with variable speed drive permanently applied to both, optimum pump operation cannot always be assured. This especially applies to the phase of lower pressure up from commissioning till AMLT is reached. This operation phase is relatively short in comparison to the whole lifetime of the plant. Hence, it is to be considered whether the relatively high investment cost of, for instance additional infinitely variable speed drives also for the high-pressure pumps in addition to those for the booster-pumps to optimize operation over this period will pay off.

An alternative could be to increase the permeate backpressure and operate the plant with higher average membrane flux during this phase. With this measure, the operating pressure could be adapted to such a degree that the pumps also remain at their optimum operation point during this time.

The increase of average membrane flux is, for instance, possible by operating the RO with fewer trains or at reduced membrane mounting of the trains during this phase. The increase of dynamic permeate backpressure (permeate throttling) leads directly to an increase of the necessary feed pressure to the membranes. The advantage of throttling at the permeate side is, that this pressure increase will not be fully lost for energy recovery as is the case for throttling on the high-pressure side, but is available for use in the energy recovery system.

An additional possibility for the operator of an RO – plant is it to change/reduce the AMLT and with it the necessary operating pressure of the RO passes. This can make sense for reducing the energy costs, but also for compensating for possibly increased fouling of the membranes. With this measure though, due to the more frequent replacement of the membranes the rate of membrane exchange and consequently plant operation costs will go up.

This relationship is typical for most measures for energy optimisation of SWRO – plants: improvement in energy use is most often offset by an increase of capital costs for equipment or possibly also rising chemical consumption.

6. Energy saving potential and payback

The measures for energy optimisation of an SWRO plant during the design and operation phases as described above indicate a potential for reducing energy consumption by up to about 1 kWh/m^3 of product. Most possibilities for energy optimisation as described above can be realised during the planning phase, during which the principal focus is selection of the energy recovery system. The remaining savings potential of up to one-third of the value quoted would be attained by fine-tuning the design and subsequent power–saving operation of the plant.

The question of course now arises of whether the cut in the plant's energy consumption that at first sight involves raising the capital expenditure can be compensated by cost savings due to the resulting lower energy consumption of the SWRO. (see Fig. 12).

If just the SWRO plant's capital expenditure is considered, this will mostly assessed as being rather doubtful. But if the energy cost saving for the whole lifetime of the plant is calculated, quite another picture emerges.

The graph in Fig. 13 for the reference plant with a capacity of 200,000 m^3/day shows, that cost saving from energy optimisation accruing at the end of a 20 year plant lifetime is considerable.

How much this saving will actually be depends, of course on the cost of electricity and is also fixed by the extent, to which energy consumption could be reduced. With annual escalation of 5%, the present value of energy savings after a 20-year plant lifetime and depending on the order of magnitude of electricity cost is between €70 and €230 millions.

If the escalation rate is raised to 10%, which may be considered as a quite realistic, the value of electricity conservation over the life of the plant will jump to between €150 and €400 millions.

This attains or even surpasses the initial capital expenditures of the complete process plant equipment of the reference SWRO plant.

Measure	Influence on				
	Product composition		SEC	Capex	Opex (without SEC)
	TDS	Boron			
Pre-treatment optimization	→	→	↓	↓	↓
Membrane with high rejection	↓	↓	↑	→ ↑	↓
Increase of recovery rates	↑	↑	↓	→ ↓	→ ↓
Reduce average flux	↑	↑	↓	↑	→
Reduce AMLT (increase MRR)	↓	↓	↓	↑	↑
No. elements per vessel	→ ↓	→ ↓	↑	↓	→ ↓
RO centre or train	→	→	→ ↑	→ ↓	→
Split partial first pass	→ ↓	→ ↓	↓	→ ↑	→ ↓
PH increase 1st & 2nd pass	→	↓	→ ↓	→	↑
Reduce pressure loss feed piping	→	→	↓	↑	→

Fig. 12. Influence of optimization measures on product composition and capital and operation cost.

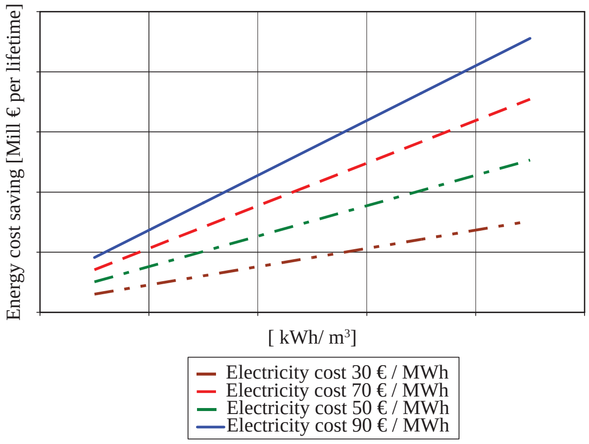

Fig. 13. Possible cost savings during SWRO plant lifecycle by energy optimization – Plant capacity 200,000 m^3/d – Electricity cost escalation rate 5%/year.

Hence, systematic reduction of the energy consumption of an SWRO plant is not only an environmental protection measure, but also contributes quite substantially to cutting of the lifetime cost of such a plant improving its economics.

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