Desalination and Water Treatment
www.deswater.com

21 (2010) 138–147
September

doi: 10.5004/dwt.2010.1302

The energy demand for desalination with solar powered reverse osmosis units

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Received 30 April 2009; accepted 2 March 2010

ABSTRACT

There are few energy recovery devices (ERD) available on the market for small reverse osmosis units (RO). With reference to small units, installations have been considered which could be driven easily by a photovoltaic (PV) generator with an output of 200 litres up to 10 m^3 desalinated water per day [1–14]. In this paper, a systematic analysis for typical reverse osmosis concepts is presented which allows better understanding of the energy demand of small RO processes with energy recovery and which can be used as a decision tool. In contrast to publications already in existence which compare energy recovery devices [9,10,12,15–27], the smallest devices are considered here. These are often positive displacement devices [3,10,16,28,29]. The new method of analysis takes as a basis the same physical parameters for all RO concepts, starting with the calculation of the osmotic pressure. Assumptions by an expert for possible operating parameters (recovery ratio, the feed and the concentrate pressure), known as the hydraulic envelope (suggested by Manth and Oklejas [30]) are not required. All parameters are considered dependent on the recovery rate. The following RO concepts are analysed:

- without energy recovery (noER)
- with energy recovery via
  - reverse running pump or turbine (ER-EC)
  - pressure exchanger (ER-PE)
  - intermittent operation with pressure storage (ER-BP)
  - pressure intensifier (ER-PI)

These basic concepts are compared for steady state operation. The analysis shows the ideal recovery ratio related to the specific energy consumption (SEC) for each RO concept. With this basic analysis it is possible to choose the most energy-efficient hydraulic concept for a specified RO capacity in order to combine it with a solar energy supply. In particular variable operation and frequent shutdowns and start-ups are typical requirements for small PV-RO systems without energy storage. The best performance in this calculation is achievable for the RO process with pressure exchanger.

Keywords: Energy efficiency; Specific energy consumption; Seawater desalination; Photovoltaic reverse osmosis system

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1. Introduction

The information available from manufacturers of ERDs for small RO systems is not suitable for direct comparison and often confusing. This situation makes the choice difficult for the user. Small direct coupled PV-RO systems for seawater desalination have challenging requirements for the hydraulic components. Low specific energy consumption for the overall system is necessary to minimize the cost of the PV generator. The system has to cope with a variable supply of power and has to perform well even in dynamic operation and frequent part load conditions [11,13]. In contrast to ''normal'' RO processes, a direct coupled PV-RO system has to cope with frequent shutdown and start-up situations. The small flow rates allow the efficient use of positive displacement machines such as high pressure pumps and energy recovery devices. These devices are compared to each other by a systematic approach.

In this work an analysis is realized which takes into account all energy consuming processes such as raw water pumping including pre-treatment, high pressure pumps, and similar components for different hydraulic concepts. The required pressure for the desalination is calculated for all systems in the same way and with the same input parameters. So the calculated specific energy consumptions are comparable. The direct comparison allows a better understanding and an assessment of the basic RO concepts with ERDs for PV-RO requirements.

2. Objective

A systematic approach to calculate and compare all kinds of hydraulic concepts for RO processes is to be introduced. In particular the theoretically achievable overall specific energy consumption of some sophisticated positive displacement devices used for energy recovery in very small RO systems will be classified with this method. Parameter variations will clarify the part load behaviour of the different concepts and allow an evaluation with regard to the aptitude of hydraulic RO concepts for PV-RO applications.

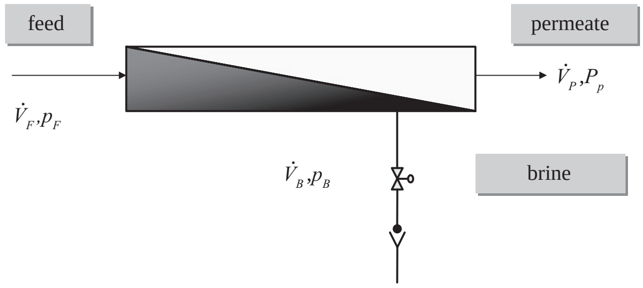

Fig. 1. RO concept without energy recovery (noER).

3. Materials and methods

3.1. Identified basic RO concepts

Five basic RO concepts were identified and examined in detail. Seawater intake and pre-treatment are considered in the calculation, but not shown in the simplified sketches. The concept without ER (Fig. 1) is considered as the reference process. The whole feed water flow is pressurized in the high pressure pump. The brine is expanded at a valve.

The basic idea of an RO concept with multiple energy conversion (ER-EC) is shown in Fig. 2. Using an energy converter (turbo-machine or hydraulic motor), potential energy from the concentrate is changed in several steps (kinetic, shaft) back into potential energy in the high pressure pump. There are various possibilities for realization for every basic concept. For example, there are solutions like the one in Fig. 2(a), where the high pressure centrifugal pump, the electric motor and a Pelton turbine are mounted on a single

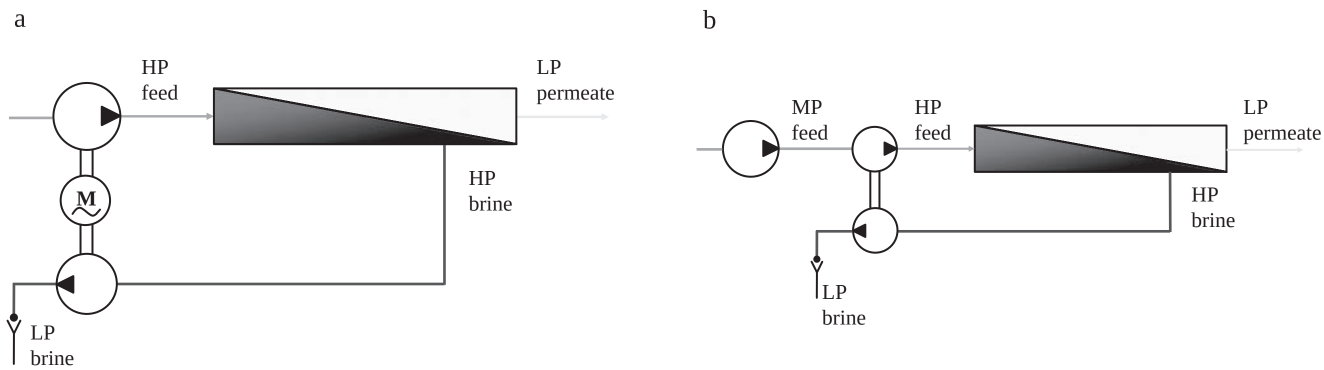

Fig. 2. (a) ER-EC with single shaft and (b) ER-EC with turbocharger and separated pump.

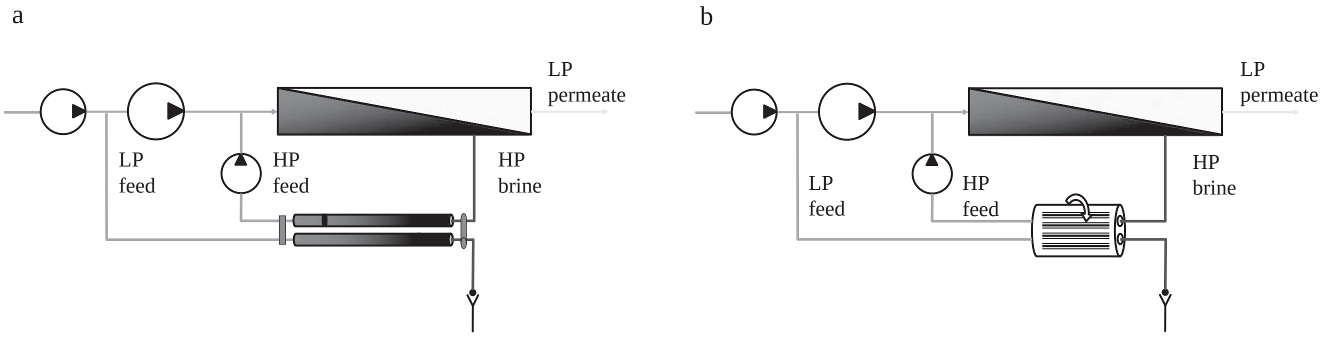

Fig. 3. (a) RO concept with a valve controlled pressure exchange unit (ER-PE). (b) RO concept with rotary pressure exchange unit (ER-PE).

shaft [21,31]. For smaller mass flows, this concept is realized with a positive displacement pump and a hydraulic motor realized as an inverse running positive displacement pump [29]. A third variation consists of a medium pressure pump and a turbocharger [21,22]. In this case the ERD is hydraulically driven by the high pressure brine and the medium pressure feed flow (Fig. 2(b)).

Fig. 3 shows the RO concepts with pressure exchange units, which are frequently installed (ER-PE). The valve controlled (Fig. 3(a)) [18,32–38] and the rotary (Fig. 3(b)) device [39–44] can be calculated using the same approach. The RO concept with a single pressure vessel for the brine (ER-BP) is suitable for very small direct coupled solar systems. The operation of direct coupled PV-RO systems will be interrupted at least once a day after sunset. A very simple batch process without sophisticated valve control and without permanent refilling of the PE device is feasible (Fig. 4).

All concepts with pressure exchange allow direct contact of the brine with the feed water. In some cases a piston is used to prevent mixing of the fluids. The basic principle is the same in all three cases: valve controlled or rotary ER-PE and ER-BP. The brine can transfer its potential energy directly to the feed.

The characteristic difference between the PE and the PI concepts is that the PI concept always uses a double-acting piston with different areas for the brine and the feed side. The ratio of these two piston areas determines the recovery ratio of the system. The high pressure brine helps to increase the pressure on the feed side via force balancing, which takes place across the whole system. A recirculation pump is not needed. Many variations of this system exist [3,10,16, 17,45,46]. The simplest device works with only one piston (PowerSurvivor; Katadyn). The highly sophisticated Clark pump works with a double piston [12,16]. A three piston device realized the the company Enercon [46] and Spectra Watermakers (Pearson pump). Most applications have installed the rod in the direction of the high pressure brine and push out the feed with the piston (category ‘‘pressure intensifier PI’’ in Fig. 6). There is additional energy needed to raise the pressure to level of the feed pressure. Bermudez-Contreras and Thomson [16] turned around this principle with their modified Clark pump. The rod is directed to the feed site and no additional energy is needed to achieve the feed pressure. Fig. 5 shows the ER-PI concept with a Clark pump and a high pressure

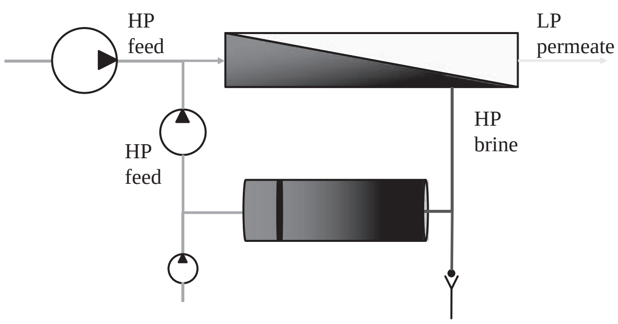

Fig. 4. RO concept with a brine pressure vessel for a batch process (ER-BP).

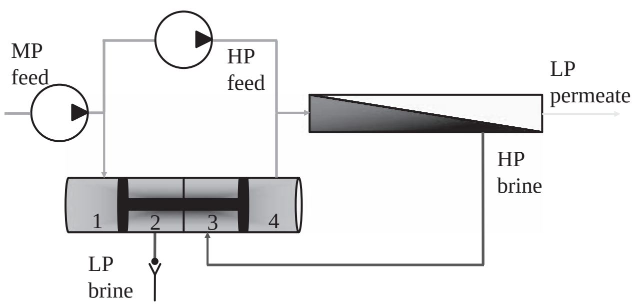

Fig. 5. RO concept with pressure intensifier (ER-PI).

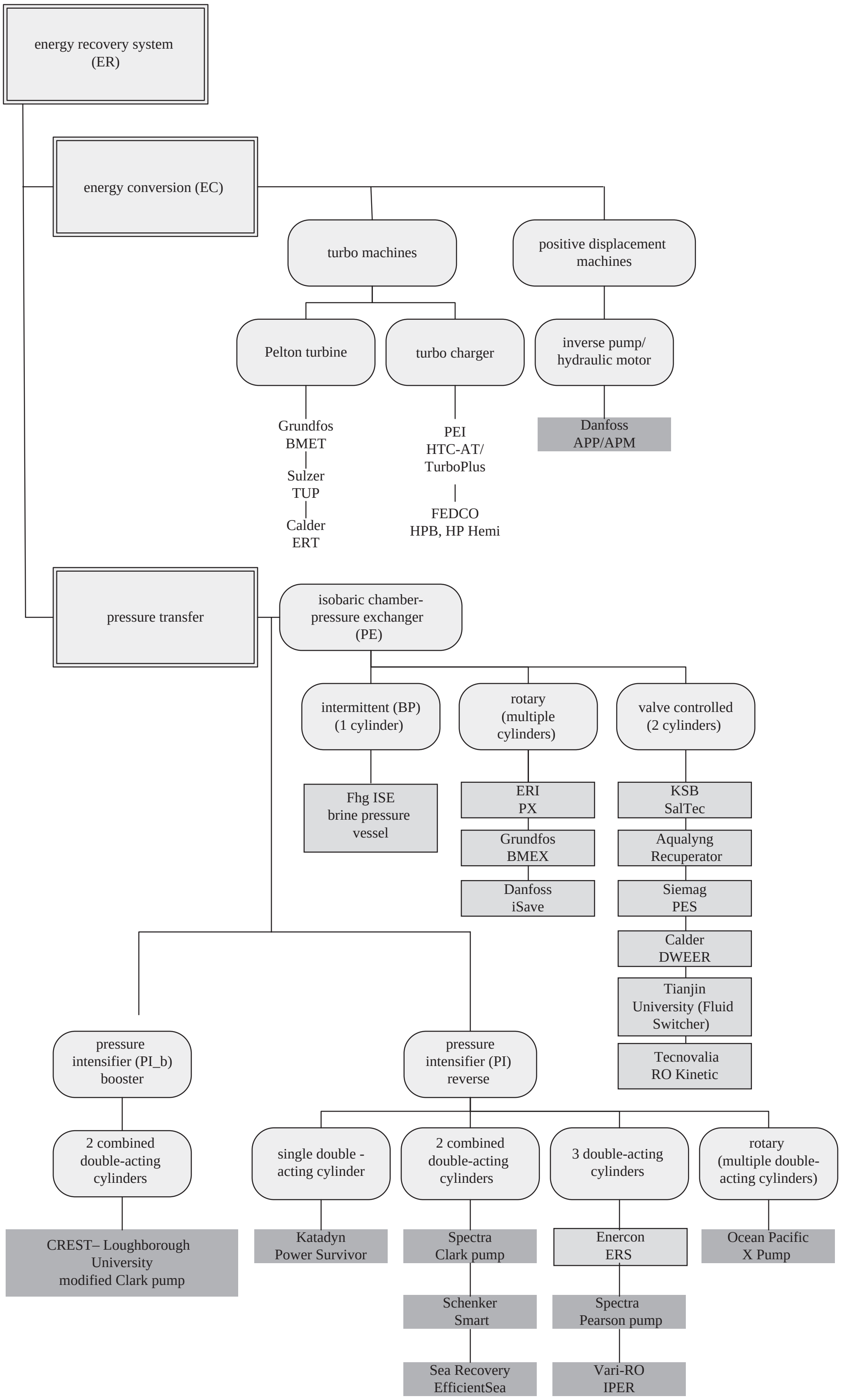

Fig. 6. Overview of energy recovery systems in the market sorted by their physical principle with examples of known products and companies; light hatching: suitable in principle; not available in the market or not available in the needed magnitude; dark hatching: suitable and available (this list is not exhaustive).

Table 1
Efficiencies used for pumps with electrical motor and ERDs

Index	Function	Efficiency used	Pressure head [10^5 Pa]	Type of flow
Pumps				
HPP	High pressure pump	60%	f(ϕ); 40-75	permeate
LPP	Low pressure pump: refilling / pretreatment	40%	0,5 / 3	Feed
MPP	Medium pressure pump	40%	f(ϕ); 5-15	Feed
RCP	Booster pump/recirculation pump	35%	f(ϕ); ~ 1	Brine
ByP	Bypass pump for variable recovery ratio in PI concept	60%	f(ϕ); 40-75	Additional feed
ERDs				
EC_HPP	High pressure pump	80%	f(ϕ); 40-75	Feed
EC_HM	Hydraulic motor	80%	f(ϕ); 40-75	Brine
			pressure level [10^5 Pa]	
PE	Pressure exchanger	65%	f(ϕ); ~ 65	Brine
BP	Brine pressure vessel	60%	f(ϕ); ~ 65	Brine
PI	Pressure intensifier	90%	f(ϕ); ~ 65	Brine

pump in a bypass to realize a variable recovery ratio first suggested by Thomson [12]. More than three double-acting pistons can be arranged as radial or axial piston pump (X pump; Ocean Pacific Technologie).

Fig. 6 shows an overview of all known types of energy recovery systems sorted by their physical principle and with their appropriate market product.

3.1.1. Analysis tool

An analysis tool was developed for comparison of the identified basic concepts concerning their specific energy consumption. The calculation is based on the following assumptions:

- steady-state operation,
- input parameters: daily production of desalted water, seawater concentration,
- calculation of the required feed pressure p_F with a factor 1.1 of the osmotic pressure of the brine π_B as a function of seawater concentration c_F and recovery ratio ϕ [47] (equation 1)
- calculation of the osmotic pressure with a retention of 99% according to van't Hoff [47]:

$$p_F = 1,1 \cdot \pi_B(c_F, \varphi) \text{ with } \varphi = \frac{\dot{V}_P}{\dot{V}_F}. \quad (1)$$

The salt concentration of the feed c_F used for this calculation is 35 g/l.

- calculation of all missing flow rates via given permeate flow and the recovery rate,
- calculation of the pressure drop over the length of the membrane module via the model of the friction loss in a tube at laminar flow conditions (Eq. (4)),
- The pressure drop is calculated for a tube with a diameter causing the same pressure drop that is caused by the membrane module (Eq. (5)),
- consideration of all energy consuming components (feed pump and pre-treatment, high pressure pumps, recirculation pumps, etc.),
- the specific energy consumption for the basic concepts is calculated with:

$$\mathrm{SEC} = \frac{\sum_i P_i}{\dot{V}_P} = \frac{\sum_i \frac{\dot{V}_i(\varphi)\cdot\Delta p_i}{\eta_i}}{\dot{V}_P}. \quad (2)$$

The efficiency values used for the calculation are listed in Table 1.

First the calculation of the specific energy consumption SEC for the reference concept without energy recovery will be shown in detail.

$$\mathrm{SEC}_{\mathrm{noER}}(\varphi) = \mathrm{SEC}_{\mathrm{pt}}(\varphi) + \mathrm{SEC}_{\mathrm{noER.RO}}(\varphi)$$

with

$$\mathrm{SEC}_{\mathrm{pt}}(\varphi) = \frac{p_{\mathrm{pt}}}{\varphi \cdot \eta_{\mathrm{LPP}}} \text{ and } \mathrm{SEC}_{\mathrm{noER.RO}}(\varphi) = \frac{p_F(\varphi)}{\varphi \cdot \eta_{\mathrm{HPP}}} \quad (3)$$

For the pressure difference in the pre-treatment stage p_{pt} 3×10^5 Pa are used. The efficiencies of the components are listed in Table 1.

Eq. (4) shows how the concept with multiple energy conversion shown in Fig. 2(a) is calculated

$$\mathrm{SEC}_{\mathrm{EC}}(\varphi) = \mathrm{SEC}_{\mathrm{pt}}(\varphi) + \mathrm{SEC}_{\mathrm{EC}}(\varphi)$$

with,

$$\mathrm{SEC}_{\mathrm{ER-EC}}(\varphi) = \frac{p_{\mathrm{F}}(\varphi)}{\varphi \cdot \eta_{\mathrm{EC.HPP}}} - \left(\frac{1}{\varphi} - 1\right) \cdot p_{\mathrm{K}}(\varphi) \cdot \eta_{\mathrm{EC.HM}},$$
$$p_{\mathrm{K}}(\varphi) = p_{\mathrm{F}}(\varphi) - \Delta p(\varphi),$$
$$\Delta p(\varphi) = \frac{128 \cdot \eta}{\pi} \cdot \frac{L_{\mathrm{module}}}{d^4_{\mathrm{tube.lam}}} \cdot \dot{V}_{\mathrm{P}} \cdot \left(\frac{1}{\varphi} - 1\right) \tag{4}$$

The tube diameter $d_{\mathrm{tube.lam}}$ is a theoretical substitution for the inner flow cross-section of the membrane module to calculate the pressure loss depending on the concentrate flow. It is defined by Eq. (5) via the friction loss in a tube at laminar flow conditions. The tube diameter is calculated using the data from an adequate membrane module. In this example, the data for the dow filmtec SW30HR LE-4040 is used [48]. The length of the module L_{module} is 1.016 m. The membrane area A_{M} is 7.9 m^2. For the viscosity of water η the value 1×10^{-3} Pa s is used.

$$\Delta p_{\mathrm{max.module}} = \zeta \cdot \frac{\rho}{2} v^2 \cdot \frac{L_{\mathrm{module}}}{d_{\mathrm{tube.lam}}}$$

with

$$\zeta_{\mathrm{lam}} = \cdot \frac{64}{\mathrm{Re}} = \frac{64 \cdot \eta}{\rho \cdot v \cdot d_{\mathrm{tube.lam}}} \text{ and } v = \frac{\dot{V}_{\mathrm{P.module}}}{A_{\mathrm{cs}}} \tag{5}$$
$$\cdot \left(\frac{1}{\varphi_{\mathrm{module}}} - 1\right) = \frac{\dot{V}_{\mathrm{P.module}} \cdot 4}{d^2_{\mathrm{tube.lam}} \cdot \pi} \cdot \left(\frac{1}{\varphi_{\mathrm{module}}} - 1\right)$$

In the datasheet shows the pressure loss over the module with 1×10^5 Pa for certain test parameters of the membrane element dow Filmtec SW30HR LE-4040. The test parameters are a permeate flow of 6.1 m^3/day and a recovery rate of 8% [48].

The concept with the pressure exchanger shown in Fig. 3 has four consumer loads: The pretreatment pump (not shown in the figures), the filling pump, the high pressure pump and the recirculation pump. Eq. (6) shows how the specific energy consumption is calculated for all pumps. The pressure drop in the high pressure circuit is given in Eqs. (4) and (5).

$$\mathrm{SEC}_{\mathrm{PE}}(\varphi) = \mathrm{SEC}_{\mathrm{pt}}(\varphi) + \mathrm{SEC}_{\mathrm{PE1}}(\varphi) + \mathrm{SEC}_{\mathrm{PE2}}(\varphi) + \mathrm{SEC}_{\mathrm{PE3}}(\varphi)$$

with

– filling pump: $\mathrm{SEC}_{\mathrm{PE1}}(\varphi) = \dfrac{(1-\varphi) \cdot p_{\mathrm{fill}}}{\varphi \cdot \eta_{\mathrm{LPP}}}$,

– high pressure pump: $\mathrm{SEC}_{\mathrm{PE2}}(\varphi) = \dfrac{p_{\mathrm{F}}(\varphi)}{\eta_{\mathrm{HPP}}}$,

$$-\text{recirculation pump}: \mathrm{SEC}_{\mathrm{PE3}}(\varphi) = \left(\frac{1}{\varphi} - 1\right) \frac{\Delta p(\varphi)}{\eta_{\mathrm{RCP}} \cdot \eta_{\mathrm{PE}}} \tag{6}$$

For the calculation of the power for the refilling of the exchanger a pressure p_{fill} of 0.5×10^5 Pa is used. The calculation of the specific energy consumption for the pressure intensifier concept shown in Fig. 5 is more complicated. The most important equations are given in Eq. (7). The derivation of these equations can be retraced in [12].

$$\mathrm{SEC}_{\mathrm{PI}}(\varphi) = \mathrm{SEC}_{\mathrm{pt}}(\varphi) + \mathrm{SEC}_{\mathrm{PI1}}(\varphi) + \mathrm{SEC}_{\mathrm{PI2}}(\varphi)$$

with

– medium pressure pump:

$$\mathrm{SEC}_{\mathrm{PI1}}(\varphi) = \frac{p_{\mathrm{MPP}}(\varphi)}{\varphi \cdot \eta_{\mathrm{MPP}} \eta_{\mathrm{PI}}},$$

– bypass pump:

$$\mathrm{SEC}_{\mathrm{PI2}}(\varphi) = \frac{p_{\mathrm{F}}(\varphi) - p_{\mathrm{MPP}}(\varphi)}{\varphi \cdot \eta_{\mathrm{ByP}}} \cdot \left[\frac{1}{\varphi} - \frac{\varphi - 1}{\varphi(R_{\mathrm{t}} - 1)}\right] \tag{7}$$
$$p_{\mathrm{MPP}}(\varphi) = p_{\mathrm{F}}(\varphi) \cdot R_{\mathrm{t}} + p_{\mathrm{amb}}(1 - R_{\mathrm{t}}) + \frac{\beta \cdot \dot{V}_{\mathrm{P.PI}}(\varphi)}{A^2_{\mathrm{P}} \cdot R_{\mathrm{t}}} + \Delta p(\varphi)$$
$$\dot{V}_{\mathrm{P.PI}}(\varphi) = \dot{V}_{\mathrm{p}}(\varphi) \cdot R_{\mathrm{t}} \cdot \frac{\varphi - 1}{\varphi \cdot (R_{\mathrm{t}} - 1))}.$$

A geometric factor R_{t} of 0.1 for the relation of the cross section areas rod to piston is used according to [12]. For the piston area A_{P} 0.01 m^2 is used for the calculation. The ambient pressure p_{amb} is set to 1×10^5 Pa. A friction factor β of 100 N/(m/s) is used for the friction losses in the Clark pump.

The chosen efficiencies allow a realistic classification of the RO concepts. Small positive displacement

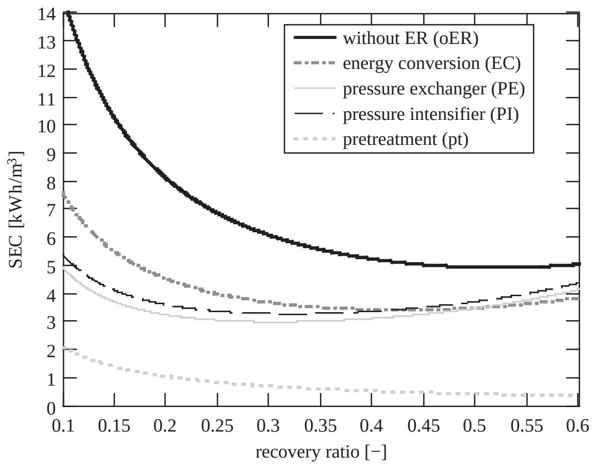

Fig. 7. Comparison of basic concepts – specific energy consumption versus recovery ratio for a seawater concentration of 35 g/l.

Table 2
Achievable specific energy consumption and corresponding best recovery ratios

Basic concept	Energetically optimal recovery ratio ϕ_{opt} [%]	Specific energy consumption SEC(ϕ_{opt}) [kWh/m^3]
noER	52	4.9
ER-EC	43	3.4
ER-PE	31	**3.0**
ER-PI	32	**3.3**

pumps like the high pressure pump or the bypass pump have an overall efficiency of 60% in the presented example. Small centrifugal pumps with lower efficiencies of 35% and 40% are assumed for the low pressure pumps or booster pumps. The used efficiencies for pumps and ERDs are given in Table 1.

4. Results and discussion

The results of the comparison are shown in Fig. 7. The seawater concentration for all calculations was assumed as 35 g/l. All concepts show a minimum value for the specific energy consumption in the range of 10% to 60% for the recovery ratio ϕ. For small values of ϕ, the power demand increases because of the higher flow rates that have to be pretreated and pumped through the system, which cause friction losses. The concentration of the brine rises for higher ϕ values. For this reason the osmotic pressure and the required feed pressure increase. The specific energy consumption has a minimum between these two extremes. The higher the efficiency of the ER concept, the lower is the optimal recovery ratio.

The ER-EC concept with high efficiencies of 80% for the hydraulic motor and the high pressure pump results in a lower improvement for low recovery ratios than the other concepts. The pumps and ERDs have to have very good efficiencies to achieve a remarkable improvement using such RO concepts. The ER-EC concepts convert the potential energy of the brine into kinetic energy of the fluid, into kinetic energy of a piston or vane, into the rotary energy of a shaft and back the same way to finally increase the potential energy of the feed. Every conversion step causes losses. The whole feed flow rate has to be pressurized in the high pressure pump, which means a high power demand. Therefore even a slightly decreased efficiency causes high losses.

The ER-PI concepts indicate a good performance despite a medium pressure pump efficiency of only 40%. Here the advantages of the direct transfer of potential energy from the brine to the feed via force balance can be seen. The ER-PE shows the best performance despite moderate efficiencies of all components. The single component has to convert only low hydraulic power. Therefore lower efficiencies at part load operation do not, as expected, cause high losses, and do not significantly increase the specific energy consumption.

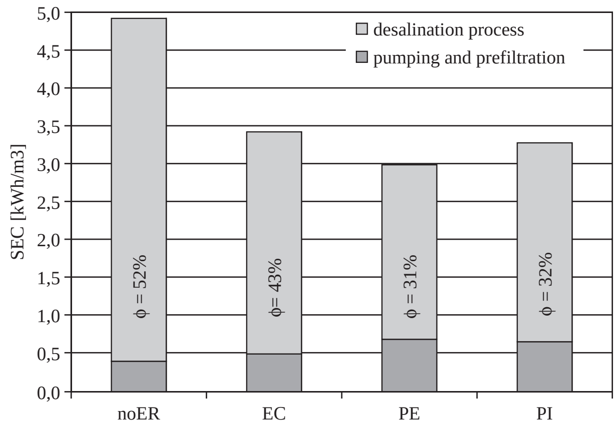

Fig. 8. Comparison of basic concepts – minimum of specific energy and corresponding best recovery ratios.

Table 2 shows minima for the achievable energy demand and the recovery ratio for the given input parameters. It has to be mentioned that in this energetic calculation, fouling and scaling is not considered. Because of the risk of scaling, it might not be recommendable to operate an RO installation at 52% recovery ratio with a seawater concentration of 35 g/l.

Further technical criteria for the selection of a PV-RO concept with ER, apart from the specific energy consumption, are:

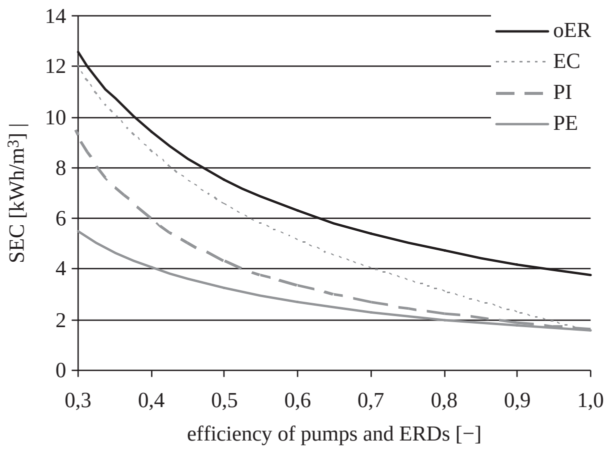

Fig. 9. Part load behaviour of RO concepts; specific energy consumption over the efficiency of pumps and energy recovery devices.

- controllability and good part load behaviour to trace the solar power availability in a direct coupled PV-RO installation,
- lifetime and maintenance effort,
- availability of the components with the required dimensions,
- easy start-up and shutdown,
- gentle closing and opening valves to avoid water hammers,
- scaling prevention,
- simple and compact design,
- flexibility to realize several recovery ratios depending on the feed water properties.

In order to examine the part load behaviour, some parameter studies have been made (Fig. 9). Therefore the same efficiency is assumed for all components. The value ''1'' means ideal pumps and an ideal energy recovery. In Fig. 9 it can be seen that with smaller efficiencies, the energy conversion concept converges rapidly towards the concept without energy recovery. The concept with pressure exchanger shows the lowest increase in specific energy consumption. A good overall performance of the PI concept with the Clark pump depends on a high efficiency of the medium pressure pump where all the power of the feed flow is transferred. Fig. 9 shows that the components of the PE concept are less sensitive to a decrease in the efficiency of the single components. This is because there is less power transferred, so that a smaller efficiency does not mean as much loss.

In reality, every component changes its efficiency in part load operation in a different way. This simple approach can help to give an insight into how the different RO concepts cope with part load operation.

5. Conclusion

The calculations reconfirm the superiority of the principle of the isobaric chamber as energy recovery for small scale RO processes. The principle of direct transfer of potential energy via double-acting pistons (PI) or direct contact (PE) is advantageous and should be taken into account when designing modern PV-RO systems with small capacities and low recovery ratios. In particular the devices using double-acting pistons (PI) could be clarified and listed in order of superiority. In spite of very good assumptions for the energy recovery device itself, the overall specific energy consumption is higher than that of the PE concept. For direct coupled PV-RO systems, it is important that the ER concept works independently from the flow rate and even has a good overall performance when the efficiency of single pump components is low at lower rotational speed (part load conditions). The PE concept can therefore cope best with a frequent part load operation due to the variable solar irradiation and frequent shutdowns and start-ups. This is because the potential energy of the concentrate flow is kept at a high pressure level, and only small amounts of energy are converted in the pump components, where losses occur.

Acknowledgements

This work is supported in part by Pairan Elektronik GmbH, IBC Solar AG, Gather Industrie GmbH, MAT Plasmatec GmbH, Katadyn Products Inc., TBB and the German Federal Ministry of Economics and Technology BMWi (16INO538). Discussions with Professor S. Ripperger and Professor R. Huss are gratefully acknowledged.

Abbreviations

Symbols

A_M	membrane area, 7.9 m^2 [48]
A_{CS}	cross section area
A_P	area of the piston, 0.01 m^2
c_F	salt concentration of the feed, 35 g/l
L_{module}	length of the RO-module, 1.016 m [48]
p_{amb}	ambient pressure, 1×10^5 Pa
p_F	feed pressure
p_{fill}	pressure for refilling of the pressure exchanger, 0.5×10^5 Pa
P_i	power demand component i
p_{pt}	pressure difference for the pretreatment, 3×10^5 Pa
Re	Reynolds number
R_t	geometric factor of the double acting piston; relation of the cross section areas rod to piston, 0.1
SEC	specific energy consumption
V	flow velocity
$\dot{V}_P$	permeate flow, 1.1 m^3/h
$\dot{V}_{P.module}$	permeate flow; test conditions, 6.1 m^3/h [48]
$\dot{V}_F$	feed flow
$\dot{V}_i$	flow for component i
$\triangle p_i$	pressure head for component i
$\triangle p_{max.module}$	pressure loss over the module at given parameters for the permeate flow and the recovery ratio, 1×10^5 Pa [48]
β	friction factor, 100 N/(m/s)
ϕ	recovery ratio
ϕ_{module}	recovery ratio; test conditions, 8%

η	viscosity of water, 1×10^{-3} Pa s
η_i	efficiency for component i, see Table 1
Π_B	osmotic pressure of the brine
ρ	density of water
ζ	friction coefficient

Abbreviations used

ByP	bypass pump
EC	energy conversion
ERD	energy recovery device
ER-EC	energy recovery with energy conversion
ER-PE	energy recovery with pressure exchange
ER-PI	energy recovery with pressure intensifier

Product names (partly copyright)

APP/APM	ER-EC concept: combination of an axial piston pump, an axial piston hydraulic motor and an electromotor on a single shaft	Danfoss
BMET	ER-EC concept: high pressure centrifugal pump and Pelton turbine	Grundfos
BMEX	valve controlled PE concept	Grundfos
Clark pump	PI concept (two pistons)	Spectra Watermakers
DWEER	ER-EC concept: combination of an axial piston pump, an axial piston hydraulic motor and an electromotor on a single shaft	Calder AG, former Desal
EfficientSea	PI concept (two pistons)	Grundfos
BMEX	rotary PE concept	Sea Recovery
ERS	PI concept (three pistons)	Enercon
Fluid Switcher	valve controlled PE concept	University Tianjin
HPB	EC concept (turbo booster)	FEDCO
HP-Hemi	EC concept (turbo booster with auxiliary motor)	FEDCO
iSave	rotary PE conept in combination with booster pump	Danfoss
Pearson pump	PI concept (three pistons)	Spectra Watermakers
PES	valve controlled PE concept	Siemag
PowerSurvivor	PI concept (one piston)	Katadyn
PX	rotary PE concept	ERI - Energy Recovery Inc.
Recuperator	valve controlled PE concept	Aqualyng
RO Kinetic	valve controlled PE concept	Tecnovalia
SALTEC	valve controlled PE concept	KSB AG
Smart	PI concept (two pistons)	Schenker Watermakers
Turbo Plus	Turbocharger	PEI - Pump Engineering Inc.
Vari-RO	PI concept (three pistons)	IPER
X Pump	PI concept (multiple pistons)	Ocean Pacific Technologies

HM	hydraulic motor
HP	high pressure
HPP	high pressure pump
LP	low pressure
LPP	low pressure pump
MPP	medium pressure pump
noER	without energy recovery
noER.RO	without energy recovery only RO-systems
PE	pressure exchange
PI	pressure intensifier
pt	pretreatment
PV	photovoltaic
RCP	recirculation pump
RO	reverse osmosis

References

[1] A. Al-Karaghouli, D. Renne, and L.L. Kazmerski, Technical and economic assessment of photovoltaic-driven desalination systems. Renewable Energy, 35 (2) (2010) 323–328.

[2] A. Bermudez-Contreras, M. Thomson, and D.G. Infield, Renewable energy powered desalination in Baja California Sur, Mexico. Desalination; European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort 22 - 25 April 2007, Halkidiki, Greece, European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort, 2008. 220 (1–3). p. 431-440.

[3] W.D. Childs et al., VARI-RO solar-powered desalting technology. Desalination; European Conference on Desalination and the Environment, 1999. 125 (1–3), pp. 155–166.

[4] D. Herold, et al., Small scale photovoltaic desalination for rural water supply – demonstration plant in Gran Canaria. Renewable Energy; 6th Arab International Solar Energy Conference: Bringing Solar Energy into the Daylight, 1998, 14 (1–4), pp. 293–298.

[5] D. Herold and A. Neskakis, A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria. Desalination,137 (1–3) (2001) 285–292.

[6] A. Joyce, et al., Small reverse osmosis units using PV systems for water purification in rural places. Desalination, 137 (1–3) (2001) 39–44.

[7] B.G. Keeper, R.D. Hembree and F.C. Schrack, Optimized matching of solar photovoltaic power with reverse osmosis desalination. Desalination, 54 (1985) 89–103.

[8] E.S. Mohamed et al., The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; experimental and economical evaluation. Desalination; Desalination and the Environment,184 (1–3) (2005) 241–246.
[9] E.S. Mohamed, et al., An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with a hydraulic energy recovery unit. Desalination,194 (1–3) (2006) 239–250.
[10] M. Thomson, M.S. Miranda and D. Infield, A small-scale seawater reverse-osmosis system with excellent energy efficiency over a wide operating range, Desalination, 153 (1–3) (2003) 229–236.
[11] M. Thomson and D. Infield, A photovoltaic-powered seawater reverse-osmosis system without batteries, Desalination, 153 (1–3) (2002) 1–8.
[12] M. Thomson, Reverse-Osmosis Desalination of Seawater Powered by Photovoltaic without Batteries. 2003, Loughborough University.
[13] M. Thomson and D. Infield, Laboratory demonstration of a photovoltaic-powered seawater reverse-osmosis system without batteries. Desalination; Desalination and the Environment, 183 (1–3) (2005) 105–111.
[14] E. Tzen, K. Perrakis and P. Baltas, Design of a stand alone PV – desalination system for rural areas. Desalination; Papers presented at the Conference on Membranes in Drinking and Industrial Water Production, Vol. 119 No. (1–3), 1998, pp. 327–333.
[15] W.T. Andrews and D.S. Laker, A twelve-year history of large scale application of work-exchanger energy recovery technology. Desalination, 138 (1–3) (2001) 201–206.
[16] A. Bermudez-Contreras and M. Thomson. Modified operation of a small scale energy recovery device for seawater reverse osmosis. in European Desalination Conference: Desalination for the Environment - Clean Water and Energy. 2009. Baden-Baden, Germany: European Desalination Society.
[17] A. Bermudez-Contreras and M. Thomson, Unified analysis of pressure-transfer energy recovery devices for seawater reverse osmosis. submitted to Desalination and Water Treatment, 2009.
[18] S. Bross and W. Kochanowski, SWRO core hydraulic module – the right concept decides in terms of energy consumption and reliability Part II. Advanced pressure exchanger design. Desalination; Desalination Strategies in South Mediterranean Countries, Vol. 165, 2004, pp. 351–361.
[19] C. Harris, Energy recovery for membrane desalination. Desalination; European Conference on Desalination and the Environment, 125 (1–3) (1999) 173–180.
[20] W.A.G. Hoeting, Seawater reverse osmosis with energy recovery. Desalination, 40 (3) (1982).357–361.
[21] T. Manth, M. Gabor, and J. Oklejas Eli, Minimizing RO energy consumption under variable conditions of operation. Desalination; Desalination and the Environment: Fresh Water for all, 157 (1–3) (2003) 9–21.
[22] E. Oklejas, Energy Efficiency Considerations for RO plants: A Method for Evaluation. The International Desalination and Water Reuse Quarterly, 2002, 11(4), pp. 26–34.
[23] B. Orchard, Finding the Holy Grail of reverse osmosis. World Pumps, (484) (2007) 20–23.
[24] L. Souari and M. Hassairi, Sea water desalination by reverse osmosis: the true needs for energy. Desalination; EuroMed 2006 - Conference on Desalination Strategies in South Mediterranean Countries, 2007. 206 (1–3), pp. 465–473.
[25] J. Sun, et al., Performance prediction of hydraulic energy recovery (HER) device with novel mechanics for small-scale SWRO desalination system. Desalination, 249 (2) (2009) 667–671.
[26] X. Wang, et al., Comparative study on stand-alone and parallel operating schemes of energy recovery device for SWRO system. Desalination, 254 (2010) 170–174.
[27] A.M. Farooque, et al., Comparative Study of various Energy Recovery Devices used in SWRO Process. 2004.
[28] W.D. Childs and A.E. Dabiri, Hydraulic Driven RO Pump & Energy Recovery Systems. Desalination and Water Reuse, 9(2) (1999) 21–29.
[29] A. Valbjørn, ERD for small SWRO plants. Desalination, 248 (1–3) (2009) 636–641.
[30] T. Manth and E. Oklejas. RO energy consumption under variable parameters of operation. in Biennial AMTA Conference. 2002. Tampa, Florida, USA.
[31] P. Goubeau and P. Guinard, Energy recovery pump in reverse osmosis desalination plants. Desalination, 54 (1985) 117–126.
[32] O.M. Al-Hawaj, The work exchanger for reverse osmosis plants. Desalination; Desalination and the Environment: Fresh Water for all, 157 (1–3) (2003) 23–27.
[33] L. Drabløs, Aqualyng(TM) – a new system for SWRO with pressure recuperation. Desalination, 139 (1–3) (2001) 149–153.
[34] P. Geisler, et al., Pressure exchange system for energy recovery in reverse osmosis plants. Desalination; The International Workshop on Desalination Technologies for Small and Medium Size Plants With Limited Environmental Impact, 1999. 122(2–3), pp. 151–156.
[35] P. Geisler, W. Krumm, and T.A. Peters, Reduction of the energy demand for seawater RO with the pressure exchange systems PES. Desalination, 135(1–3) (2001) 205–210.
[36] B. Peñate, J.A. de la Fuente, and M. Barreto, Operation of the RO Kinetic® energy recovery system: Description and real experiences. Desalination, 252 (2010) 179–185.
[37] S.A. Shumway, The Work Exchanger for SWRO Energy Recovery. Desalination and Water Reuse, 8(4) (1999) 27–33.
[38] J. Sun, et al., Energy Recovery Device with a Fluid Switcher for Seawater Reverse Osmosis System. Chin. J. Chem. Eng. 16 (2) (2008) 329–332.
[39] Energy recovery device is designed to make desalination affordable. Membr. Technol., 2008 (4) (2008) 9–10.
[40] I.B. Cameron and R.B. Clemente, SWRO with ERI's PX Pressure Exchanger device – a global survey. Desalination; European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort 22 -25 April 2007, Halkidiki, Greece, European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort, 2008, 221 (1-3), pp. 136–142.
[41] L.J. Hauge, The pressure exchanger – A key to substantial lower desalination costs. Desalination; Proceedings of the American Desalting Association 1994 Biennial Conference and Exposition Membrane and Desalting Technologies, 102 (1–3) (1995) 219–223.
[42] L.J. Hauge, The Pressure Exchanger. Desalination and Water Reuse, 9(1) (1999) 54–60.
[43] J.P. MacHarg, Retro-fitting existing SWRO systems with a new energy recovery device, Desalination, 153 (1–3) (2003) 253–264.
[44] R.L. Stover, Seawater reverse osmosis with isobaric energy recovery devices. Desalination; EuroMed 2006 - Conference on Desalination Strategies in South Mediterranean Countries, 2007. 203 (1–3), pp. 168–175.
[45] W.D. Childs and A.E. Dabiri, Desalination cost savings of VARI-RO(TM) pumping technology. Desalination, 87 (1–3) (1992) 109–135.
[46] F. Hensel and K. Uhl, Low energy desalination and wind energy – sustainable solutions for drinking water production. Desalination; Desalination Strategies in South Mediterranean Countries, 168 (2004) 125–126.
[47] T. Melin and R. Rautenbach, Membranverfahren; Grundlagen der Modul- und Anlagenauslegung. VDI-Buch. Vol. 3. 2007, Springer. 584.
[48] dow. Filmtec SW30HRLE-4040. 2010 [cited 14.Jan 2010].