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Multiple Reverse Osmosis sub-units supplied by unsteady power sources for seawater desalination

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ABSTRACT

A major drawback of Reverse Osmosis (RO) desalination units is their poor performance at off-design conditions. On the other hand, they can operate with low specific energy consumption and produce high-quality fresh water when they are supplied with almost constant power, according to their design and nominal operating conditions. This aspect brings additional effort when there is the need to desalinate seawater or even brackish water using unsteady power sources, such as renewable energy systems powered by, for example, solar or wind energy. In order to overcome this issue, an alternative small-scale RO unit is investigated here, whose major advantage is that it can operate with almost constant specific energy consumption and produce high-quality fresh water with low Total Dissolved Solids (TDS) for a wide range of power input. Such unit is suitable to be combined with small-scale energy systems, which can have a very high variety on their power output, such as PV, wind turbines, or even solar Organic Rankine Cycle, for power production. The developed RO unit includes three identical sub-units, each placed on its own skid and with a fresh water capacity of 0.7 m^3/h. An energy recovery unit of axial piston motor type is equipped at each sub-unit for decreasing its power consumption. These sub-units are switched on/off, according to the power availability, in order to operate them within a range, thus with high efficiency and acceptable fresh water quality. Such small-scale RO unit, capable of producing 2.1 m^3/h of fresh water in total, is examined here, focusing on its operation, performance, and fresh water production. The main parameter adjusted is the power availability, ranging from almost zero up to the maximum value of 12 kW. The analysis first focuses on a single sub-unit, exploring its performance for variable power input, while afterwards all three sub-units are synthesized, in order to form the complete RO unit, concluding to the dependence of the fresh water production and specific energy consumption from the power supply. For the single RO sub-unit at low power input, the TDS level is very high, whereas the specific energy consumption is low, since the membrane pressure is much lower than the designed one and slightly above the osmotic pressure. For available power, more than around 1 kW, the TDS level holds acceptable values lower than 400–500 mg/l, which is achieved with the high pressurizing of the feed seawater, with specific energy consumption up to 4–5 kWh/m^3. For power input higher than 3 kW, the second and

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third sub-units are successively switched on. In this case, the specific energy consumption is almost constant and equal to 4.5 kWh/m^3, including the required power of the feed pump, while the produced fresh water TDS has small variations and is approximately equal to 200–250 mg/l.

Keywords: Reverse Osmosis; Partial load; Variable power input; Renewable energy; Membrane pressure; Energy recovery

1. Introduction

The operational and technical characteristics of a Reverse Osmosis (RO) unit are extremely important aspects, especially when its power supply is not constant. This is the common case with renewable energy systems producing power to supply RO units, at either stand-alone systems or even grid-connected [1], while several relevant studies can be found in the literature, dealing with such configurations [2–4]. Their common characteristic is that the available power feeding the RO unit substantially changes and most of the times, batteries are used in order to stabilize the power supply. The use of batteries increases the installation cost and maintenance, while it introduces some environmental issues, due to their frequent replacement [5].

If no electric storage component is considered, and the fluctuating power is directly fed to the RO unit, frequency inverters are required for the high pressure (HP) pump, in order to continually adjust its operation. Moreover, at medium/low available power, the membrane pressure will be low and the produced fresh water can be of unacceptable quality [6,7]. Moreover, at off-design conditions, both the HP pump and the energy recovery unit show decreased performance and volumetric efficiency.

In order to overcome this, an alternative RO configuration is proposed here, which can assure an acceptable fresh water quality for a wide range of power supply and with almost constant specific energy consumption. The proposed small-scale RO unit includes three identical sub-units, equipped with energy recovery units for decreasing the power consumed [8,9]. According to the power availability, the RO sub-units are switched on/off. For low power supply, only one RO skid operates, while for higher power input, the operation of the second and third sub-units is successively initiated. The operation and performance of such RO unit for variable power input is examined in this study, which can be integrated with numerous energy systems, especially with renewables (e.g. solar and wind energy), whose power production profile changes rapidly [1,2,10–12].

2. RO unit, components, and methods

2.1. RO unit design

The RO unit has been designed, considering a significant power fluctuation. If a single RO unit is used, it could produce fresh water for power input up to around 30–40% of the maximum one [13]. Such design is not suitable for many cases when the power input shows significant fluctuations. Therefore, an alternative design is followed, in order to operate efficiently at the whole load range.

The proposed configuration includes three identical RO sub-units. Each one has its own skid and control panel. According to the available power, it is decided how many sub-units operate, while they can be switched on/off accordingly. At low loads, only one sub-unit operates, whose HP pump speed can change (regulation of its frequency using an inverter). Therefore, such design can assure a good performance, even when the supplied power is very low, while producing fresh water of acceptable quality, with very low Total Dissolved Solids (TDS), around 200–250 ppm. The specific energy consumption changes within a narrow range and is around 3.5 kWh/m^3, which is a very competitive value especially among small-scale systems with capacity of few cubic meters per hour. To this value, the required power for the feed pump should be added as well. The water recovery is held constant and equal to 32%, which depends on the technical specifications of the membranes used and the capacity of the energy recovery unit components (specifically of the volume flow rate ratio of the pump and motor). The maximum fresh water production of the RO unit is 2.1 m^3/h when all three sub-units are operating, while its configuration is depicted in Fig. 1.

2.2. RO sub-unit

Each RO sub-unit includes a centrifugal feed pump (operating at constant speed/frequency), two filters, HP pump (of axial piston pump—APP type), energy recovery unit (of axial piston motor—APM type, coupled on the same shaft with the HP pump), frequency

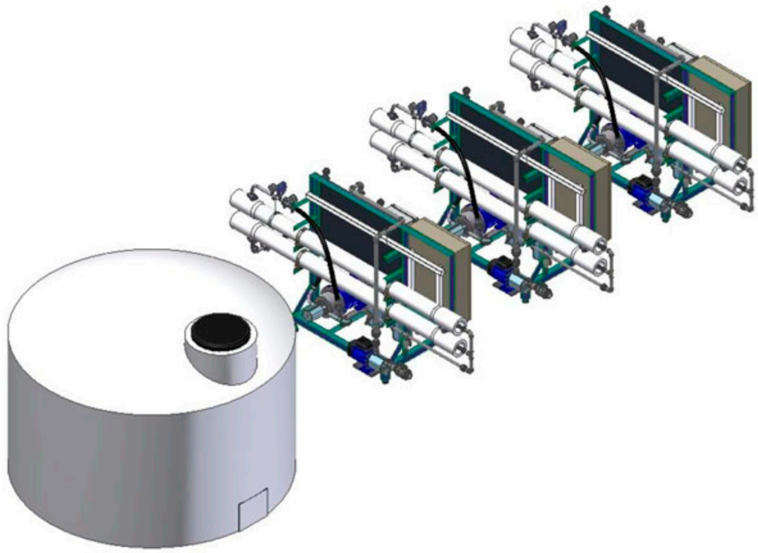

Fig. 1. Configuration of the RO unit, depicting the seawater tank and the three sub-units.

inverter for controlling the electric motor of the HP pump, membranes and membrane vessels, hydraulic pipes, and measurement/control instruments. Such RO sub-unit is depicted in Fig. 2.

A seawater tank is also used, feeding the three sub-units. A simple design of such combined configuration is depicted in Fig. 3.

Since the energy recovery unit is coupled on the same shaft with the HP pump and the electric motor, having a common rotational speed, Eq. (1) is used to describe the power conservation of the system [10,14].

$$P_{e} + P_{APM} = P_{APP} \tag{1}$$

where P_e is the power input to the electric motor of the RO sub-unit, P_{APM} is the power recovered by the axial piston motor, and P_{APP} is the power of the HP pump for pressurizing the feed seawater (for simplicity, it also includes the feed pump power).

The power demand of the HP pump is given by Eq. (2) [14].

$$P_{APP} = \frac{Q_{SW} dP}{n_{APP} n_{el}} \tag{2}$$

where Q_{SW} is the feed seawater flow rate, dP is the pressure difference at the HP pump (equal to around 50–60 bar), n_{APP} is the efficiency of the axial piston

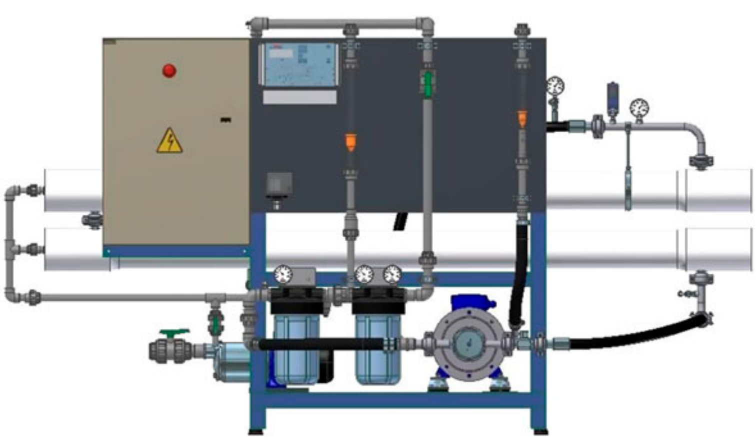

Fig. 2. RO sub-unit, depicting the HP pump, feed pump, control panel, membranes, filters, and hydraulic circuit.

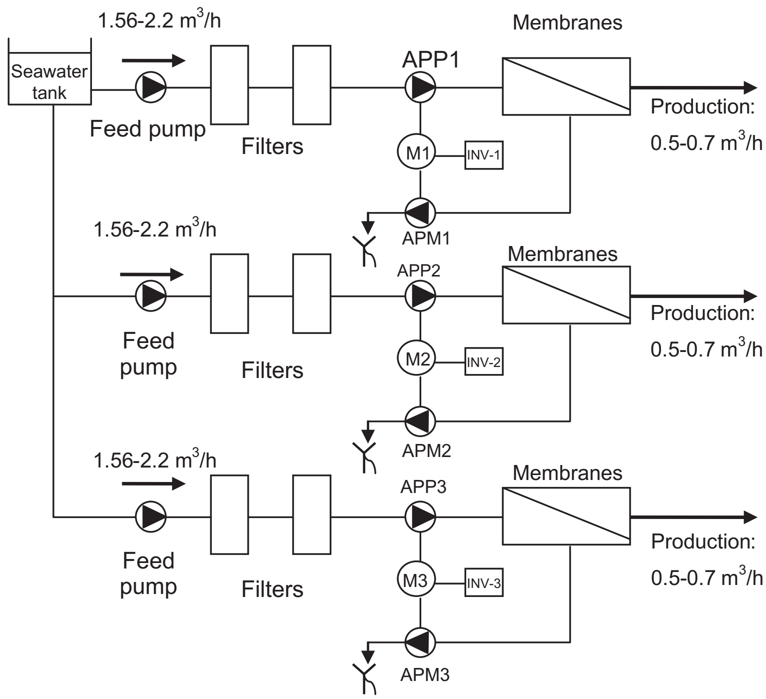

Fig. 3. RO sub-units, depicting their main components and configuration.

pump set equal to 90%, and n_{el} is the electrical efficiency of the axial piston pump equal to 86%.

The power recovered by the APM is given by Eq. (3) [14].

$$P_{APM} = Q_{BR} dP_{APM} n_{APM} \tag{3}$$

where Q_{BR} is the brine flow rate (equal to around 68% of the feed seawater flow rate, since the water recovery is 32%), dP_{APM} is the pressure difference at the axial piston motor (its outlet is considered to be equal to the ambient pressure, while its inlet is 1.5 bar lower than the membrane pressure), and n_{APM} is the efficiency of the axial piston motor equal to 75% [15].

The main performance values of each RO sub-unit are calculated using ROSA v.9.1 software [16] for an inlet seawater temperature equal to 20°C and a typical TDS equal to 42,000 mg/l, representing typical seawater of the Aegean Sea in Greece. The membranes used are of SW30-4040 type [17], with two membranes placed in series with each vessel, while two vessels are used in total. The results of the ROSA software are combined with the performance data calculated using Eqs. (1)–(3).

The performance of each RO sub-unit can be then simulated, while the correlations of the most critical parameters, such as the membranes pressure, flow rate, power input, etc., are extracted and used in the main simulation program built under the EES environment [18,19]. The main operational data of the RO configuration are depicted at the left-hand side of Fig. 4, where the membrane pressure is observed as a function of the feed seawater flow rate. The correlation between the seawater flow rate and the HP pump rotational speed is observed at the right hand side of Fig. 4.

From the left-hand side of Fig. 4, it is concluded that the correlation between the membrane pressure and the seawater flow rate is linear. At the maximum flow rate allowed, the membrane pressure takes its maximum possible value (around 62 bar), assuring a good quality of the desalinated water. Moreover, the control of the seawater flow rate is achieved with the frequency variation of the electric motor of the HP pump, using an inverter, controlling its rotational speed (maximum speed of 3,500 rpm) and regulating the seawater flow rate, as shown in the right-hand side of Fig. 4. The seawater feed pump operates at constant speed, but with variable outlet pressure since it is not essential to control its operation. By doing so, the regulation of the system becomes simpler.

3. Results and discussion

The study focuses on the RO system results, considering a variable power input at each case. This section begins with the investigation of the performance

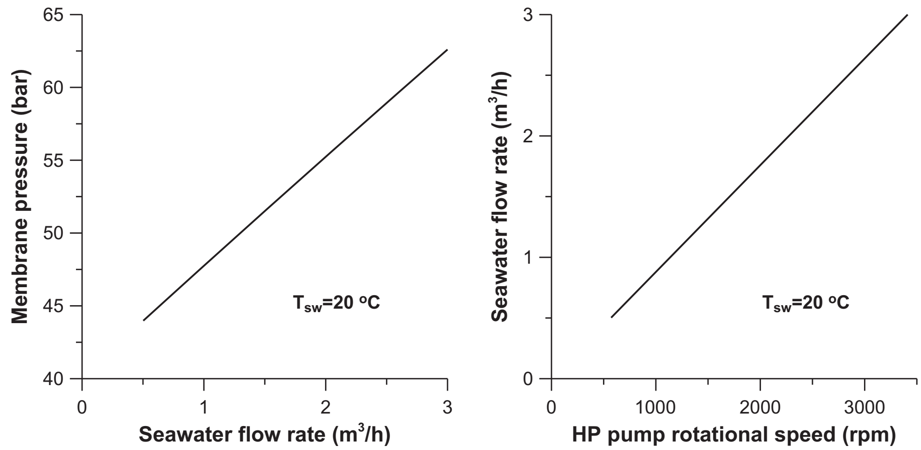

Fig. 4. Operational characteristics for each RO sub-unit. Left: RO sub-unit membrane pressure as a function of the inlet seawater flow rate. Right: Seawater flow rate as a function of the HP pump speed.

of each RO sub-unit, while then all three sub-units are synthesized, in order to examine the RO system as a function of the operating load.

3.1. RO sub-unit operation

In this section, the operation and performance of each RO sub-unit is investigated. Focus is also given on their switchable operation, according to the available power input. The characteristics curve of the membranes is shown in Fig. 5. This figure actually correlates the membrane pressure with the fresh water flow rate, enabling the calculation of the operating condition of each sub-unit. The quality of the produced water is also shown.

The membrane's pressure is almost linearly correlated to the feed flow rate (constant recovery ratio of 32%), while the salinity rapidly decreases as the flow rate increases [8,20]. Acceptable quality of fresh water (lower than 500 mg/l) is observed for fresh water flow rates higher than around 0.3 m^3/h, while the membrane pressure can reach even 62 bar.

The correlation of the membrane pressure with the specific energy consumption and the required power is shown in Fig. 6 for constant seawater feed flow rate equal to the designed one (when operating the HP

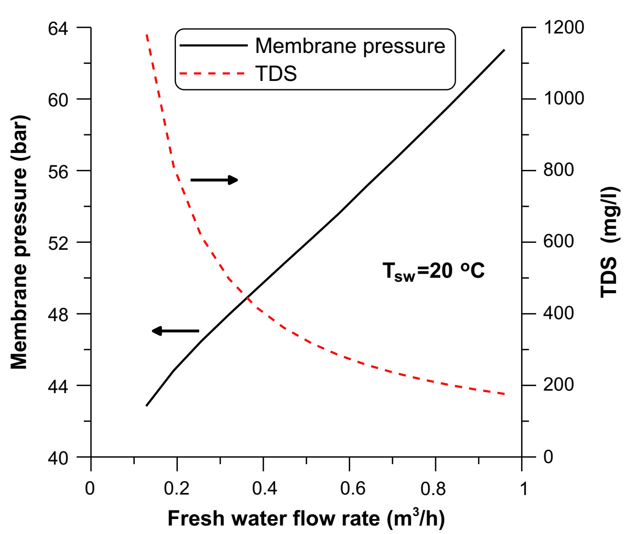

Fig. 5. Membrane pressure and salinity as a function of the fresh water flow rate for each RO sub-unit.

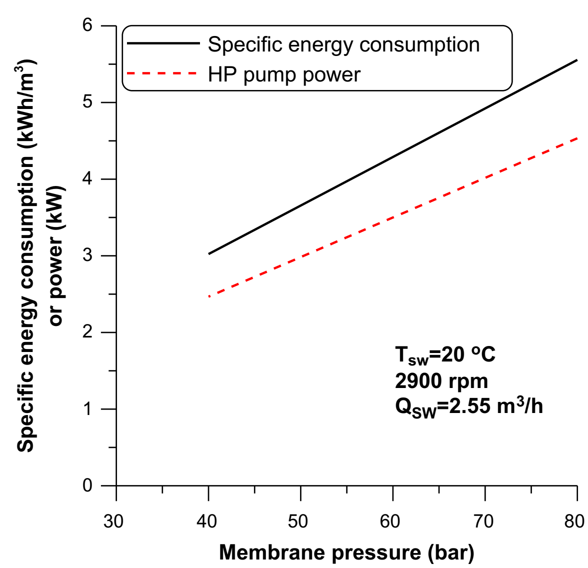

Fig. 6. Specific energy consumption and required power of each RO sub-unit as a function of the membrane pressure.

pump at 50 Hz–2,900 rpm). The power of the feed pump is not included.

At low membrane pressure, the specific energy consumption significantly decreases, but the disadvantage at this case is that the produced fresh water is of low quality (higher than 500 mg/l). Therefore, the investigation of the operation of each RO sub-unit is not only relevant to the power requirement, but also to the quality of the produced water.

A more detailed view of the characteristic curve of the HP pump is depicted in Fig. 7, where the feed flow rate and power consumption can be observed for different rotational speeds. This figure considers the membrane pressure as a free parameter, while showing that the required HP pump power is linearly correlated to the rotational speed, while it increases for higher membrane pressure, as expected.

The RO sub-unit operating condition for a given power input can be calculated when the characteristic curves of both the membranes and the HP pump are taken into consideration. Their combined operation gives the final values of the feed flow rate and membrane pressure. This can be easily accomplished if the configuration is finalized. Such method is depicted in Fig. 8, where the operating condition is actually the cross-sectional of two curves. One curve corresponds to the characteristic curve of the membranes and the other of the HP pump, while each set of curves corresponds to different power input in the range of 1–3 kW.

It can be observed that for low available power (1 kW, see left Fig. 8), the membrane pressure is less than 50 bar, while the seawater feed flow rate is around 1 m^3/h (fresh water flow is equal to 0.32 m^3/h). This operating condition is close to the lower operational limit of the sub-unit, since the pumps can operate within a flow rate range, corresponding to a frequency range of the electric motor

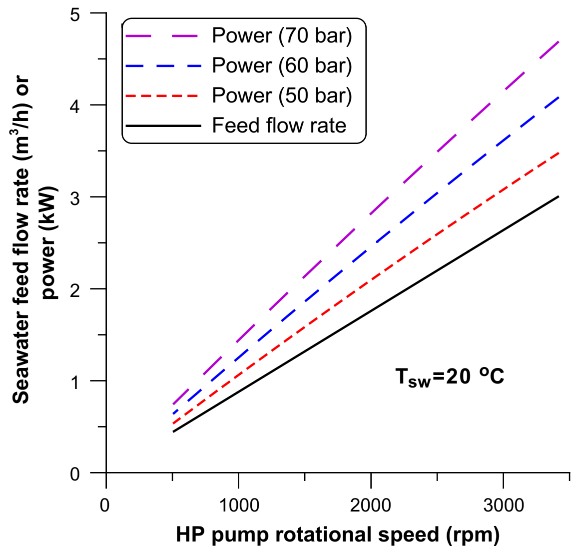

Fig. 7. Feed flow rate and consumed power as a function of the HP pump rotational speed for different membrane pressure.

used. The membrane pressure rapidly increases for higher power input (see middle Fig. 8), since the design operating condition is approached. For power input equal to 3 kW (right Fig. 8), the seawater feed flow rate is just higher than 2 m^3/h, while the membrane pressure is around 58 bar.

These correlations can be extended, concluding to Fig. 9, where the specific energy consumption can be observed as a function of the available power input for each RO sub-unit, including both the power for the HPP and the feed pump. In the same figure, the fresh water TDS is also shown.

It is observed that the TDS level has a steep variation at low available power, where the specific energy

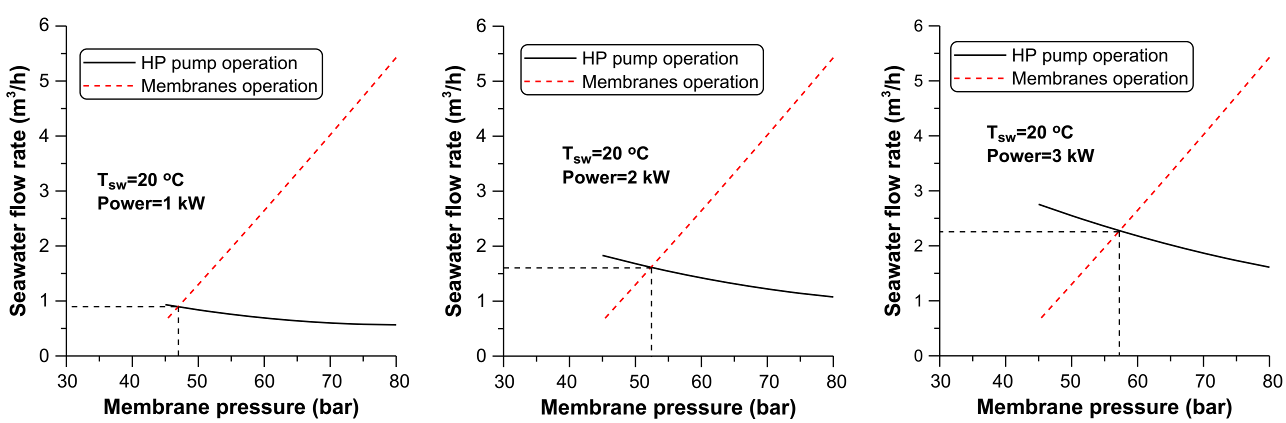

Fig. 8. Characteristic curves of RO sub-unit operation for three values of power input.

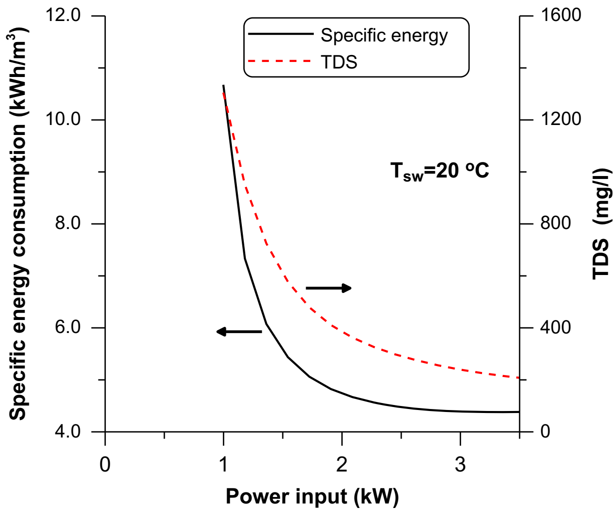

Fig. 9. Specific energy consumption and fresh water TDS of each RO sub-unit for variable power input.

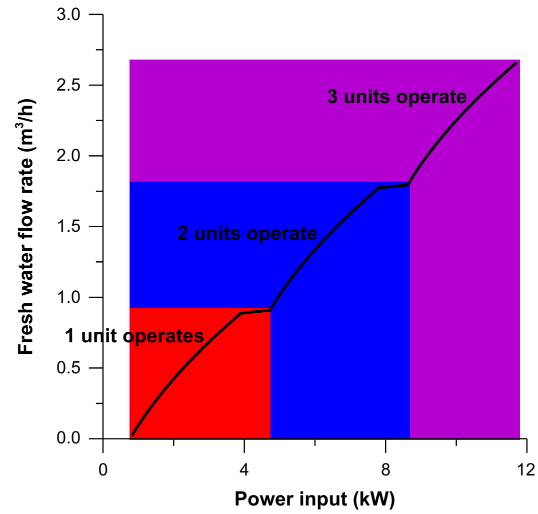

Fig. 10. Operation of RO sub-units as a function of the power input.

consumption is high, since the membrane pressure is much lower than the designed one and the produced fresh water is low [7]. For available power higher than 1.5 kW, the TDS level holds acceptable values lower than 400–500 mg/l, which is achieved with the high pressurizing of the feed seawater, increasing the fresh water flow rate and decreasing the specific energy consumption up to values of 4.5 kWh/m^3.

3.2. RO system

In the previous section, the performance and operation of a single RO sub-unit has been examined and presented. Here, the synthesis of all three sub-units is implemented, presenting the results of this alternative RO system.

It has been mentioned previously that the RO sub-units are switched on/off according to the available power. In Fig. 10, it is shown as a function of power input, the sub-units that are operating, and the fresh water production.

It is observed that for power production up to around 4 kW, only one RO sub-unit operates producing 0.7 m^3/h of fresh water. For higher power production, the second and then the third sub-unit are successively engaged, offering a high flexibility during the part-load operation. Moreover, even at very low load (e.g. at 20% of the full load, for around 2 kW), the performance of the desalination unit is adequate, producing water of acceptable quality with low specific energy consumption, as will be presented next.

In Fig. 11 the performance of the RO system for the whole range of power input is depicted. It can be clearly seen that when the available power is around 4 and 8.5 kW, the second and third RO sub-unit are switched on, respectively. This transition is not smooth, since at the beginning of their operation, the fresh water TDS is high (see Fig. 9), increasing the mixture TDS, while the specific energy consumption is low, reducing the overall value.

For power input higher than 3 kW, the specific energy consumption is almost constant and equal to 4.5 kWh/m^3, while the fresh water TDS has small variations and is approximately equal to 200–250 mg/l. For very low power input, the fresh water TDS is very

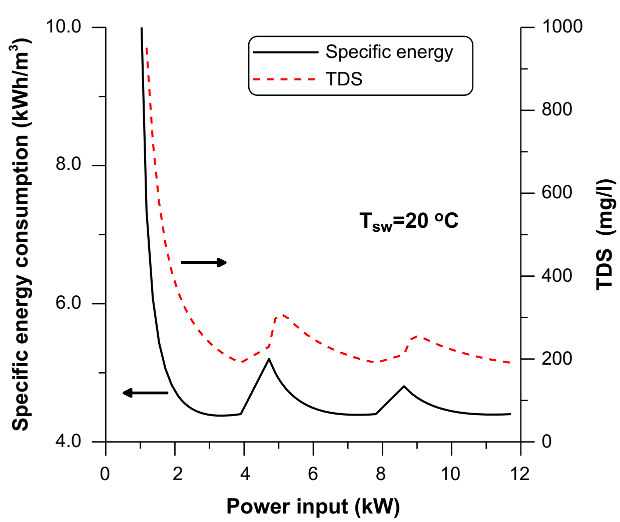

Fig. 11. Specific energy consumption and fresh water TDS of the RO system as a function of the power input.

high due to the low membrane pressure. Only for power input higher than 1.5 kW, the fresh water has an acceptable quality (around 10–15% of the total capacity).

4. Conclusions

In the present work, an alternative RO unit was investigated. Attention was given on the three identical RO sub-units and their switchable operation, according to the available power. The operation of each RO sub-unit was examined during the load variation at the whole possible range. Focus was given on the performance values, when the membrane pressure and feed flow rate change, due to the variable power availability in the range of 0–12 kW. Then, the RO system performance was identified by the synthesis of these three sub-units.

The present study focuses on the RO desalination units at variable load operation, suggesting an alternative configuration that could be utilized especially for small-scale systems supplied by renewable energy systems, which show high intermittency. The proposed configuration offers flexibility and can secure an acceptable fresh water quality at almost all operating conditions from very low load up to the maximum one. Such aspects are very important, in order to further improve such integrated systems and conclude to alternative designs, which can increase their performance and at the same time, reduce their specific water costs, enabling them to further proceed to pre-commercialization stage.

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List of symbols

dP_{APM}	—	pressure difference at the axial piston motor (bar)
dP	—	pressure difference at the HP pump (bar)
P_e	—	power input to the RO unit (W)
P_{APM}	—	power recovered by the axial piston motor (W)
P_{APP}	—	power of the axial piston pump (W)
Q_{BR}	—	brine flow rate (m^3/h)
Q_{SW}	—	feed seawater flow rate (m^3/h)
T_{SW}	—	seawater temperature (℃)

References

[1] E.S. Mohamed, G. Papadakis, Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics, Desalination 164(1) (2004) 87–97.
[2] E.M.A. Mokheimer, A.Z. Sahin, A. Al-Sharafi, A.I. Ali, Modeling and optimization of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia, Energy Convers. Manage. 75 (2013) 86–97.
[3] D.P. Clarke, Y.M. Al-Abdeli, G. Kothapalli, The impact of renewable energy intermittency on the operational characteristics of a stand-alone hydrogen generation system with on-site water production, Int. J. Hydrogen Energy 38(28) (2013) 12253–12265.
[4] A.M. Bilton, R. Wiesman, A.F.M. Arif, S.M. Zubair, S. Dubowsky, On the feasibility of community-scale photovoltaic-powered reverse osmosis desalination systems for remote locations, Renew. Energy 36(12) (2011) 3246–3256.
[5] E. McKenna, M. McManus, S. Cooper, M. Thomson, Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems, Appl. Energy 104 (2013) 239–249.
[6] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems—A technical and economical experimental comparative study, Desalination 221(1–3) (2008) 17–22.
[7] P.A. Davies, A solar-powered reverse osmosis system for high recovery of freshwater from saline groundwater, Desalination 271 (2011) 72–79.
[8] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with an hydraulic energy recovery unit, Desalination 194 (2006) 239–250.
[9] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; experimental and economical evaluation, Desalination 184(1–3) (2005) 241–246.
[10] N.G. Voros, C.T. Kiranoudis, Z.B. Maroulis, Solar energy exploitation for reverse osmosis desalination plants, Desalination 115 (1998) 83–101.
[11] G. Kosmadakis, D. Manolakos, S. Kyritsis, G. Papadakis, Simulation of an autonomous, two-stage solar organic Rankine cycle system for reverse osmosis desalination, Desalin. Water Treat. 1 (2009) 114–127.
[12] D. Manolakos, G. Kosmadakis, S. Kyritsis, G. Papadakis, On site experimental evaluation of a low-temperature solar organic Rankine cycle system for RO desalination, Solar Energy 83 (2009) 646–656.
[13] E. Dimitriou, E. Sh. Mohamed, G. Kyriakarakos, G. Papadakis, Experimental investigation of the performance of a reverse osmosis desalination unit operating under full and part load conditions, in: Presented at the WIN4Life International Conference, Tinos Island, Greece, September 19–21, 2013.
[14] A. Ghobeity, A. Mitsos, Optimal time-dependent operation of seawater reverse osmosis, Desalination 263 (2010) 76–88.

[15] D.-H. Hellmann, H. Rosenberger, E.F. Tusel, Saving of energy and cost in seawater desalination with speed controlled pumps, Desalination 139 (2001) 7–19.
[16] http://www.dowwaterandprocess.com/support_training/design_tools/rosa.htm (accessed 25 November 2013).
[17] http://www.dowwaterandprocess.com/en/products/f/filmtec_sw30_4040 (accessed 25 November 2013).
[18] S.A. Klein, Engineering Equation Solver (EES) software, Academic Professional version, 2013. Available from: http://www.fchart.com/ees/.
[19] G. Kosmadakis, D. Manolakos, G. Papadakis, An investigation of design concepts and control strategies of a double-stage expansion solar organic Rankine cycle, Int. J. Sust. Energy (2013), in press (available online), doi:10.1080/14786451.2013.827682.
[20] D. Manolakos, G. Papadakis, S. Kyritsis, K. Bouzianas, Experimental evaluation of an autonomous low-temperature solar Rankine cycle system for reverse osmosis desalination, Desalination 203 (2007) 366–374.