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Experimental comparison of the performance of two reverse osmosis desalination units equipped with different energy recovery devices

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ABSTRACT

Sea water reverse osmosis (SWRO) desalination constitutes a successful technology for covering local fresh water supply shortage in many areas of the world and especially in isolated areas such as islands and coastal regions. SWRO units can be combined with renewable energy (RE) technologies such as photovoltaic and wind generators. Small-scale SWRO units combined with energy recovery devices can decrease drastically the energy consumption of the SWRO units. Furthermore, it is proven that the operation of a desalination unit in part-load conditions can result in lower specific energy consumption compared to continuous full-load operation. This paper presents an experimental comparison between two small-scale SWRO units equipped with different energy recovery devices in order to lower the specific energy consumption. The first SWRO unit consists of a hydraulic energy recovery device of the Clark pump type which plays also the role of the high-pressure pump in a conventional reverse osmosis unit. The second SWRO unit is equipped with two types of Danfoss pumps (a rotary piston pump and a motor pump), based on the axial piston principle. The main objective of the comparison is the identification of the energy recovery device with the lowest specific energy consumption of the SWRO unit. Both units are installed at the Laboratory of Agricultural Engineering of Agricultural University of Athens and they are tested under full- and part-load conditions. The experimental operation of the SWRO units in part-load conditions is achieved by varying the speed of the motor pump assembly, the pressure and the flow rate of the feed water. During the evaluation of the measurements results, an optimum operating window was drawn regarding the operation of the SWRO desalination units in part- and full-load conditions. More specifically, the minimum measured specific energy consumption of the Clark SWRO unit was found to be 5.7 kWh/m^3 at a pressure of 44 bar while the Danfoss SWRO unit showed a minimum specific energy consumption of 4 kWh/m^3 at a pressure of 59 bar. With these results, a SWRO unit equipped with an energy recovery device operating under full- and part-load conditions is suitable for future direct connection with RE systems such as photovoltaic and wind turbines.

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1. Introduction

Water is one of the most important goods for a community in order to be able to thrive and flourish economically and socially. Many areas of the world, especially isolated areas such as islands and coastal regions, are deprived of fresh water. As a result water is imported from other parts of the country or even from abroad. An alternative solution to the problem is the implementation of seawater reverse osmosis (SWRO) desalination.

In the last decade, a constant increase of the share of renewable energy (RE) penetration is observed. Photovoltaics and wind generators have been successfully combined with SWRO desalination units and have shown excellent results, such as low specific energy consumption and minimal maintenance requirements [1,2]. Experimental studies have shown that small-scale SWRO desalination units combined with energy recovery devices can decrease drastically the specific energy consumption of the SWRO units [3,4]. Similar studies showed that the specific energy consumption is lower when a SWRO unit operates at part-load conditions compared to full load [5,6]. Hence, such systems are possible for interconnection with RE technologies. SWRO units powered by photovoltaic and/or wind turbines and equipped with energy recovery devices deliver excellent efficiency over a wide operating range [2,7–9].

This paper presents an experimental comparison between two small-scale SWRO units equipped with different energy recovery devices in order to lower the specific energy consumption. The first SWRO unit consists of a hydraulic energy recovery device of the Clark pump type which plays also the role of the high-pressure pump in a conventional reverse osmosis unit. The second SWRO unit is equipped with two types of Danfoss pumps (a rotary piston pump and a motor pump), both based on the axial piston principle. The main objective of the comparison is the identification of the energy recovery device with the lowest specific energy consumption of the SWRO unit. Both units are installed at the Laboratory of Agricultural Engineering of Agricultural University of Athens and they are studied in part- and full-load operation. The knowledge gained through this experimental work will allow the future direct connection of SWRO units equipped with energy recovery devices with RE systems such as photovoltaic and/or wind turbines.

2. Description of the SWRO desalination units

2.1. First desalination system description

The first SWRO desalination unit is described in detail in reference [5], generally, it consists of two 25–40 inch spiral wound seawater Filmtec membrane modules. An AC feed water motor pump assembly, drives the NaCl solution (50 mS/cm) from the mixing tank to the hydraulic energy recovery device of the Clark pump type, which plays also the role of the high-pressure pump in a conventional reverse osmosis unit. The configuration of the system is presented in Fig. 1. The system works in a closed water loop circuit to avoid continuous solution preparation.

2.2. Hydraulic energy recovery device (Clark pump)

The Clark pump replaces the high-pressure pump in a conventional desalination unit. The Clark pump is a very elegant brine stream energy recovery device. It recovers the energy contained in the high-pressure brine stream and returns it directly to the feed flow. More specifically, the feed water motor pump assembly pressurizes the feed water from the main mixing tank to one of the two cylinders of the Clark pump. The high-pressure brine enters to the second Clark pump cylinder and exchanges its hydraulic pressure; the result of these actions is the intensification of the feed water pressure to the required membrane pressure (around 50–60 bar). The technical specifications of the Clark pump are shown in Table 1.

2.3. Second desalination system description

The second desalination system consists of a mixing tank, feed water pump, pretreatment system, high-pressure pump equipped with two types of Danfoss pumps, and four 25–40 inch spiral wound seawater Filmtec membrane modules. The system works in a closed water loop circuit to avoid continuous solution preparation. A detailed description of the sub-systems and components is given below in Fig. 2.

2.3.1. Feed water tank

The NaCl solution, which is prepared by the de-chlorinated tap water, was stored in a black polyethylene tank with a capacity 1 m^3. The electrical

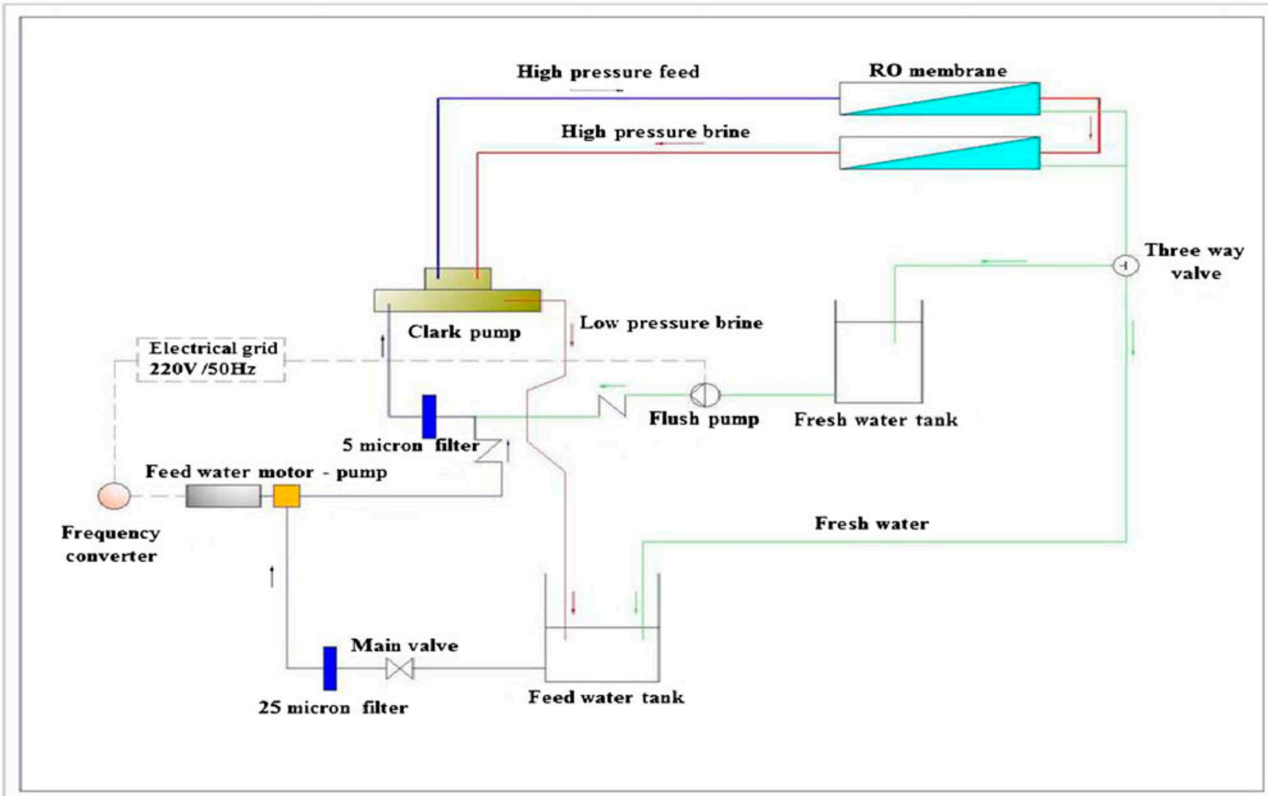

Fig. 1. Schematic diagram of the first desalination system.

Table 1
Technical specifications of the Clark pump

Parameter	Value
Type	Eco systems Clark pump
Model	E-25/590
Rated feed flow rate	760 L/h
Product water flow rate	90 L/h
Rated operating pressure	50 bar
Rated operating feed pressure	12 bar

conductivity of the feed water was adjusted at 50 mS/cm.

2.3.2. Feed water motor pump assembly

The feed water is driven from the mixing tank to the system through the feed water motor pump assembly. The motor pump assembly is a stainless steel vertical multistage pump with an AC motor, which provides the positive low pressure required at the inlet of the high-pressure pump. The technical characteristics of the feed water motor pump assembly are presented in Table 2.

2.3.3. Pretreatment system

To increase the efficiency and lifetime of reverse osmosis systems, effective pretreatment of the feed water is required. The pretreatment system of the RO desalination unit consists of three filters, described in detail in [4].

2.3.4. High-pressure motor pump assembly (Danfoss)

After pretreatment, the feed water passes to the main RO pump which is equipped with two types of Danfoss pumps (a rotary piston pump and a motor pump), both based on the axial piston principle. The motor pump operates as an energy recovery device because it gives the mechanical energy from the high-pressure brine to the rotary pump and provides the high pressure required by the membranes to overcome the high osmotic pressure of the feed water. The high-pressure motor pump assembly consists of an AC motor equipped with a frequency converter, responsible for the variable speeding conditions of the rotary piston pump. The technical specifications of the high-pressure pump are shown in Table 3.

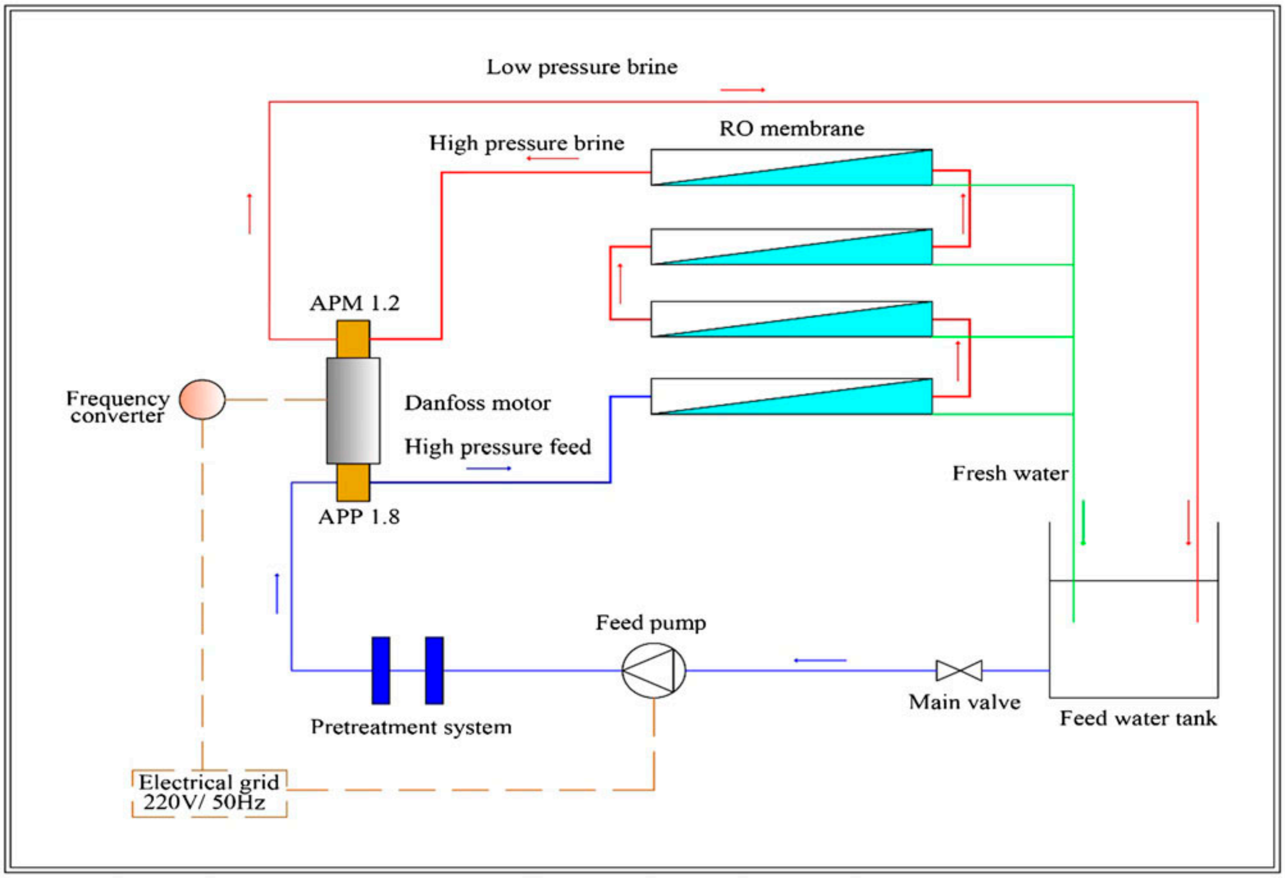

Fig. 2. Schematic diagram of the second desalination unit.

Table 2
Technical characteristics of the feed water motor pump assembly

Feed water pump	
Pump type	Single head pump
Model	1SV27N0024T
Maximum pressure	3.9 bar
Rated flow rate at 1,450 RPM	0.9 m^3/h
Motor specifications	
Motor type	SM471B14/302
Rated power	0.25 kW
Voltage	Single phase, 230 V

2.3.5. Membranes

The RO desalination unit consists of four spiral wound seawater Filmtec membrane elements connected in series in order to increase the recovery rate of desalinated water. The membrane is the "heart" of the desalination unit and separates the feed water stream into two output streams: low-salinity product water and high-pressure brine. The RO membrane's technical characteristics are shown in Table 4.

Table 3
Technical specifications of the Danfoss pump

APP pump/APM motor	
Type	APP 1.8/APM 1.2
Feed flow	0.85 m^3/h
Maximum pressure	70 bar
Permeate flow at 1,450 RPM	0.27 m^3/h
Motor specifications	
Rated power	1.5 kW
Voltage	3-phase, 380 V

2.4. Differences between two desalination systems

The main difference between two SWRO desalination systems is the energy recovery devices. The first SWRO unit consists of a hydraulic energy recovery device of the Clark pump type which plays also the role of the high-pressure pump in a conventional reverse osmosis unit. The second SWRO unit is equipped with two types of Danfoss pumps (a rotary piston pump and a motor pump), based on the axial

Table 4
RO membrane specifications [10]

Parameter	Value
Housing	Code line
Membrane type	Filmtec SW 30-2540
Maximum operating pressure	69 bar
Maximum operating temperature	45°C
Maximum feed flow rate	1.4 m^3/h
Product water flow rate	83 L/h
Salt rejection	99.2%
Single element recovery	8%

piston principle. Furthermore, the capacity of the first SWRO unit is lower than the second which is equipped with two membrane elements while the second has four membrane elements. However, the specific flux that is, the fresh water flow per unit membrane surface area and per unit of pressure at the membrane inlet is expected to be comparable for both systems.

3. Experimental comparison

3.1. Aims of the experiment

The aim of the experimental comparison was to study the performance of both energy recovery devices at part-load conditions and also to identify the energy recovery device with the lowest specific energy consumption. Thus, several parameters were measured and recorded such as a feed/concentrate flow rate, feed/concentrate electrical conductivity, membrane inlet pressure, and the specific energy consumption of both SWRO desalination units. Both units are installed at the Laboratory of Agricultural Engineering of Agricultural University of Athens and they were studied under full- and part-load operation. The experimental operation of the SWRO units in part-load conditions is achieved by varying the speed of the motor pump assembly and thus, the pressure and the flow rate of the feed water. In order for this to be achieved, the motor of both units is equipped with a frequency converter to control the rotational speed.

3.2. Membrane inlet pressure

The controlled variable through the frequency converter is the motor operation frequency, which is the means of controlling the operation point of desalination unit. The regression analysis of the experimental data showed a nearly linear relationship between the frequency of the AC motor and the membrane inlet pressure for each desalination unit with a correlation coefficient value of 99% (Fig. 3). As it can be seen in Fig. 3, the membrane inlet pressure of the desalination unit with Danfoss pumps is higher than the membrane inlet pressure of the desalination unit with Clark pump due to the capacity of the unit (larger pump and motor sizes).

3.3. Specific flux

Fig. 4 shows the specific flux of both desalination units which follows a linear relationship. When the frequency of the motor is increased, the membrane inlet pressure is raised, thus, the specific flux is also increased (Fig. 4). Due to the fact that the desalination units have different capacity and number of membrane elements, the comparison was done taking into account the active area of the membrane elements and the membrane inlet pressure. As it can be seen in Fig. 4, the specific flux for both desalination units is practically the same in the range of 41–55 bar. It can also be seen in Fig. 4 that the specific flux of the Danfoss desalination unit continues to increase after the value of 55 bar due to the different water recovery rates of the two desalination units (10% for the Clark desalination unit and 32% for the Danfoss pumps).

3.4. Fresh water quality

The fresh water quality as a function of the membrane inlet pressure can be observed in Fig. 5. As shown in Fig. 5, the electrical conductivity of the desalinated water is inversely proportional to the membrane inlet pressure. By increasing the membrane inlet pressure, the rejection of salts increases and therefore, the fresh water electrical conductivity is decreased. The difference between the two electrical conductivities of the desalination units, observed in Fig. 5, is a result of the difference in membrane inlet pressure between the two desalination units (see Fig. 3). The water is considered drinkable at a membrane inlet pressure of about 42 bar, since its electrical conductivity is lower than the limit (650 μS/cm) set by the World Health Organization (WHO) [11].

3.5. Specific energy consumption

The specific energy consumption was calculated with the following equation:

$$S_{EC} = \frac{E_m}{Q_p} \tag{1}$$

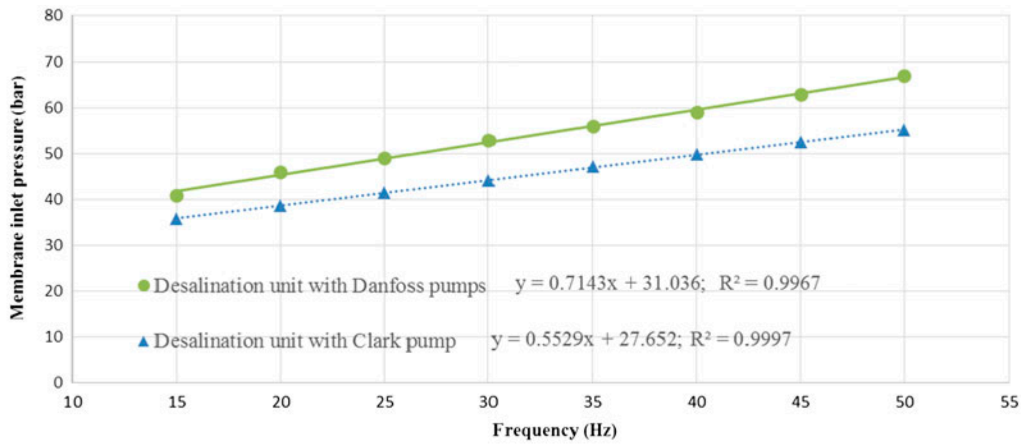

Fig. 3. Membrane inlet pressure as a function of the frequency of the motor.

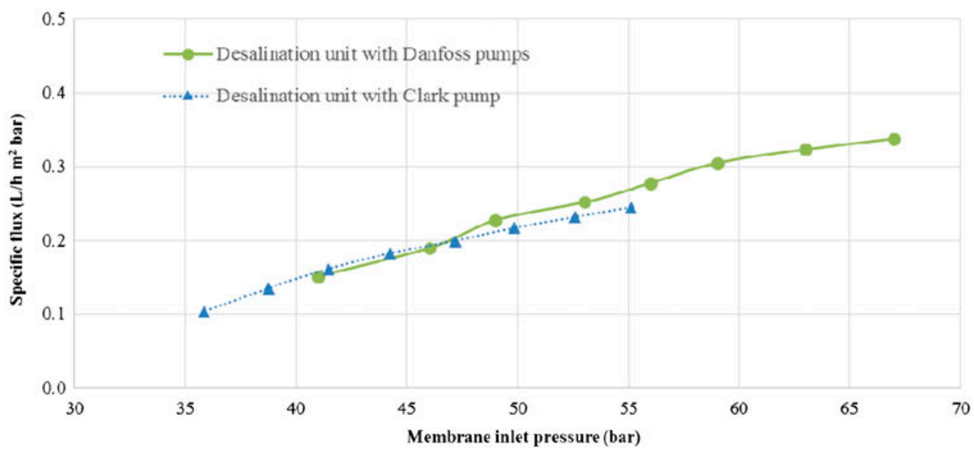

Fig. 4. Specific flux as a function of the membrane inlet pressure.

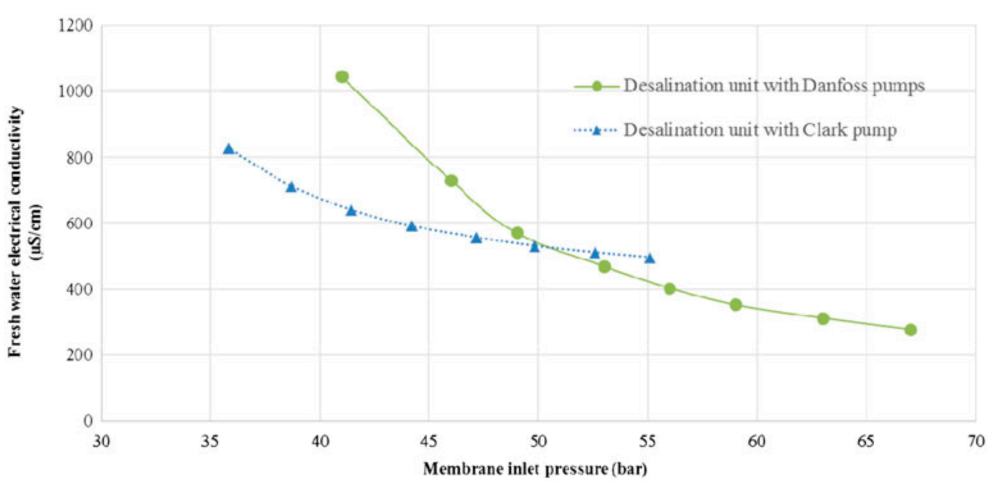

Fig. 5. Fresh water quality as a function of the membrane inlet pressure.

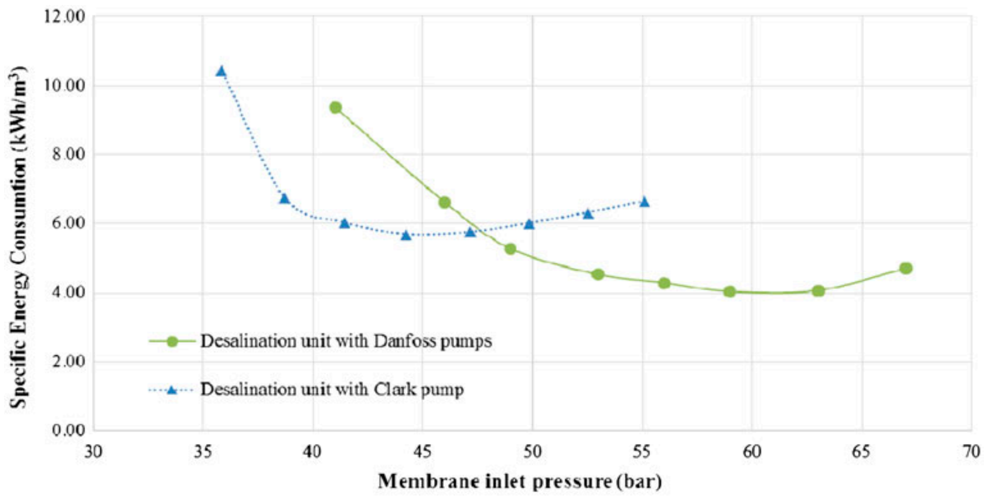

Fig. 6. Specific energy consumption.

where S_{EC} is the specific energy consumption (kWh/m^3), E_m is the energy consumed by the motor (kWh), and Q_p is the fresh water production (m^3).

As it has been found in previous similar studies [5], the specific energy consumption, shown in Fig. 6, presents a minimum at an operation pressure which is lower than the nominal operating pressure. The lowest and the highest operating points can be defined by taking into consideration that the water needs to be safe for drinking i.e. water having electrical conductivity lower than 650 μS/cm. Thus, there is an operation window for each desalination unit which ranges from approximately 40 bar up to 57 bar for the Clark desalination unit and from 49 to 67 bar for the Danfoss desalination unit (Fig. 6), which correspond to a set frequencies from 25 to 50 Hz (see Fig. 3). For this operating window, the specific energy consumption is lower than 6.6 kWh/m^3 for the first SWRO unit and 5.3 for the second SWRO unit with an acceptable quality of desalinated water (<650 μS/cm) (see Fig. 5). It is worth mentioning that the specific energy consumption of the Danfoss desalination unit was calculated by taking into account both motors of the unit. As it is already mentioned the second SWRO desalination unit consists of two motors (the feed water motor and the high-pressure motor). Therefore, the comparison between these two desalination units must be done for the total energy which is consumed by each desalination unit. It is clear that the specific energy consumption values of the Danfoss desalination unit are lower than that of the Clark desalination unit (4–9.4 kWh/m^3 and 5.5–10.4 kWh/m^3, respectively), see Fig. 6. The lower values of the specific energy consumption of the Danfoss unit can be attributed to fact that the design of the energy recovery device of the Danfoss pump is compact, which minimizes the losses of energy. As it can also be seen in Fig. 6, there is a reduction of about 16% of the specific energy consumption relative to the nominal conditions (55 bar for the Clark unit and 67 bar for the Danfoss unit) for both desalination units when they operate in part-load conditions, which is a characteristic operation property of the unit that could be utilized in coupling these desalination units with RE technologies.

4. Conclusions

The results arising from this work could be used for a direct connection of a SWRO unit equipped with a recovery device operating in full- and part-load conditions with RE systems such as photovoltaics and wind turbines.

- Small-scale SWRO desalination units equipped with energy recovery devices can drastically reduce the specific energy consumption.
- During the operation of each SWRO desalination units in part-load conditions, an operating window is identified approximately 40–57 bar for the Clark desalination unit and 49–67 bar for the Danfoss desalination unit where for the first SWRO unit, the specific energy consumption is between 6 and 6.6 kWh/m^3 with a minimum of 5.7 kWh/m^3 at 44 bar of inlet membrane pressure and for the second SWRO unit between 5.3 and 4.7 kWh/m^3 with a minimum of 4 kWh/m^3 at bar of inlet membrane pressure. The electrical conductivity of the desalinated water is within

the limits of WHO (<650 μS/cm) when both systems are operated within these inlet membrane pressure limits.

- The specific energy consumption of the Danfoss desalination unit is lower than that of the Clark desalination unit due to the different configuration of two SWRO systems regarding the energy recovery devices.
- The operation of each desalination unit in part-load condition can cause a 16% reduction of the specific energy consumption relative to the nominal conditions (55 bar for the Clark unit and 67 bar for the Danfoss unit).

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Symbols

S_{EC} — specific energy consumption (kWh/m^3)
E_m — electrical energy consumed by the motor (kWh)
Q_p — fresh water production (m^3)

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