EXPERIMENTAL COMPARISON OF THE PERFORMANCE OF TWO REVERSE OSMOSIS DESALINATION UNITS EQUIPPED WITH ENERGY RECOVERY DEVICES

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Abstract

Sea Water Reverse Osmosis (SWRO) desalination constitutes a successful technology for covering the 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 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 optimum selection of the energy recovery device with the lowest specific energy consumption of the SWRO unit. Both units are installed in the Laboratory of Agricultural Engineering of Agricultural University of Athens in 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, 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 its rotational speed.

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 measured specific energy consumption of the SWRO units was experimentally found less than 8 kWh/m^3 with an average value of fresh water production of 60 L/h and an acceptable fresh water electrical conductivity of 550 μS/cm. Despite the fact that the desalination unit with Danfoss pumps has showed lower specific energy consumption than the desalination unit with Clark pump, the size of the Danfoss pumps are designed for SWRO units with production capacity of at least 140 L/h, while SWRO units equipped with Clark pump can be as small as 60 L/h.

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 renewable energy systems such as photovoltaic and wind turbines.

Keywords: Sea Water Reverse Osmosis Desalination, Energy recovery, Variable operating conditions

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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 is imported from other parts of the country or even from abroad. As an alternative, a Sea Water Reverse Osmosis (SWRO) desalination implementation occurs to be a solution to this issue.

In the last decade a constant increase of the share of Renewable Energy (RE) penetration is observed. From its conception the utilization of a small-scale SWRO desalination unit driven by renewable energy technologies such as photovoltaic and wind generators was chosen, since it presents excellent results, such as low specific energy consumption and minimal maintenance requirements [1, 2]. In the research path, 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 renewable energy 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), based on the axial piston principle. The main objective of the comparison is the optimum selection of the energy recovery device with the lowest specific energy consumption of the SWRO unit. Both units are installed in 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 the lower intensive SWRO unit with renewable energy 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 Figure 1. The system works in a closed water loop circuit to avoid continuous solution preparation.

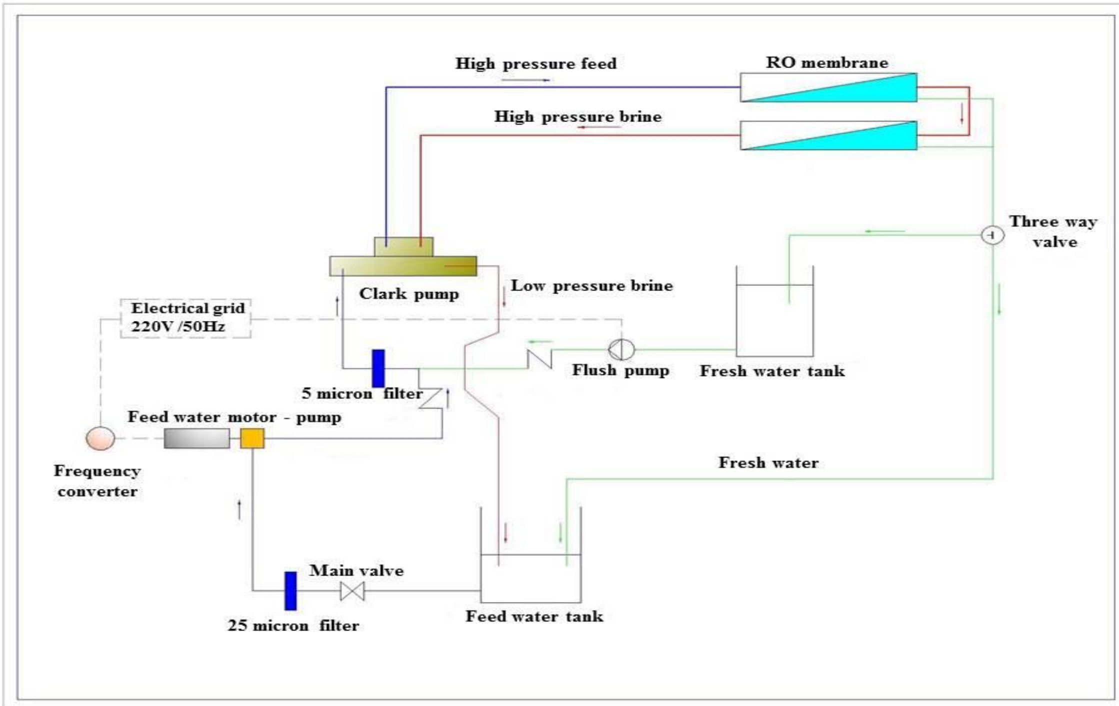

Figure 1: Schematic diagram of the first desalination system

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 mechanical energy from the 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.

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

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. (Figure 2). A detailed description of the sub-systems and components is given below.

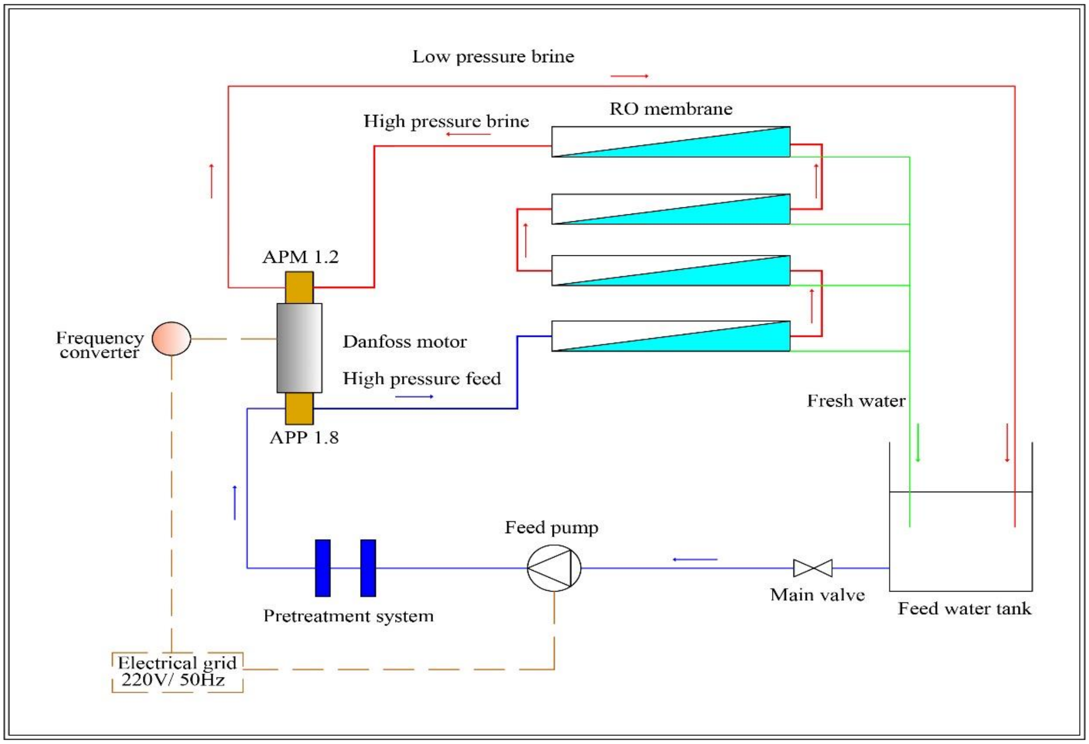

Figure 2: Schematic diagram of the second desalination unit

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 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.

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

2.3.3 Pretreatment system

To increase the efficiency and life – time 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), based on the axial piston principle. The motor pump operates as an energy recovery device because 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.

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

2.3.5 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 technical characteristics are shown in Table 4.

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 ^{o}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%

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 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 is comparable.

3 Experimental comparison

3.1 General Description

The aim of the experimental comparison was the optimum selection of the energy recovery device with the lowest specific energy consumption of the SWRO unit. 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 in the Laboratory of Agricultural Engineering of Agricultural University of Athens in 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, 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% (Figure 3). As it can be seen in Figure 3 the membrane inlet pressure of the desalination unit with Danfoss pumps is higher than membrane inlet pressure of the desalination unit with Clark pump due to the capacity of the unit.

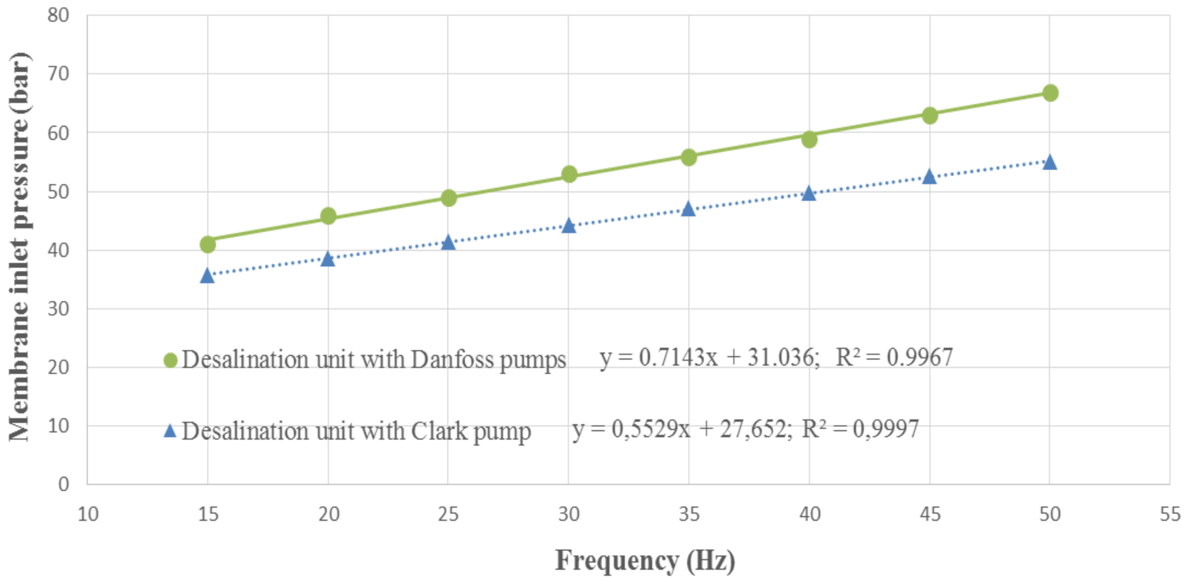

Figure 3: Membrane inlet pressure as a function of the frequency of the motor

3.3 Specific flux

Figure 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. (Figure 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 also seen in Figure 4, the specific flux of the Clark desalination unit is lower than the Danfoss desalination unit, due to the different of the low water recovery rate of the Clark desalination unit.

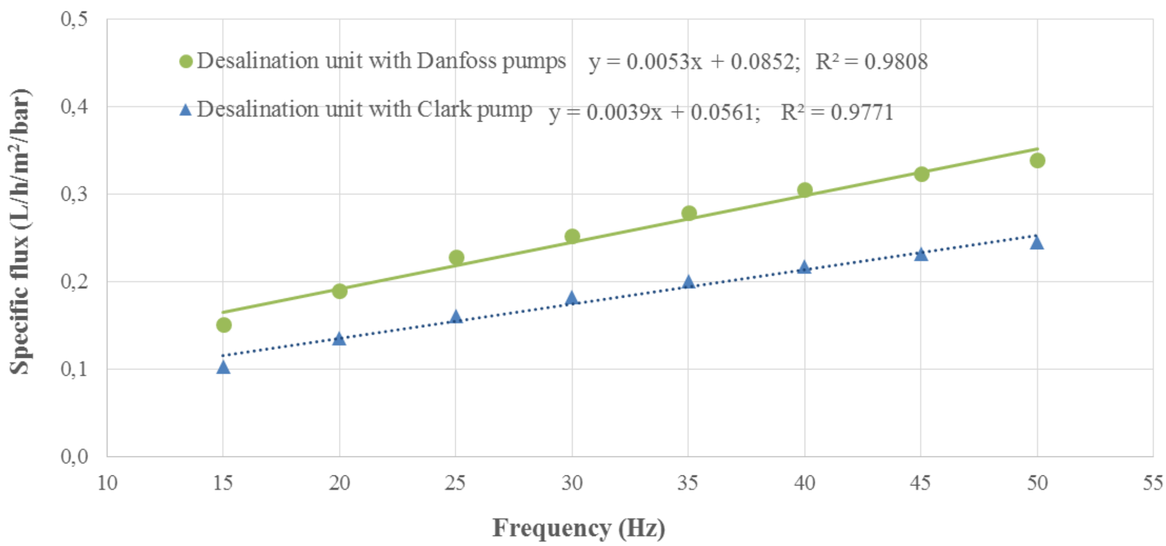

Figure 4: Fresh water flow rate as a function of the frequency of the motor.

3.4 Fresh water quality

The fresh water quality as a function of the frequency of the motor can be observed in Figure 5. As indicated in Figure 5 the frequency of the motor and corresponding the membrane inlet pressure is inversely proportional to the electrical conductivity of the desalinated water. Increasing the membrane inlet pressure increses the rejection of salts and therefore the fresh water electrical conductivity is dicreased. The differencce between two electrical conductivities of the desalination units, observed in Figure 5, is a result of the difference in membrane inlet pressure between two desalination units (see Figure 3). It is worth mentioning that the membrane's life affects the quality of the desalinated water due to the flow factor. Thus another reason of this difference is that the membranes of Clark desalination unit have already been used for 8 years comparing to the membranes of the Danfoss desalination unit which are used for the first time. The water is considered drinkable at the frequency of 18.5 Hz, which corresponds at the membrane inlet pressure higer than 42 bar, since it is lower than the limits (650 μS/cm) set by the World Health Organization (WHO) [11].

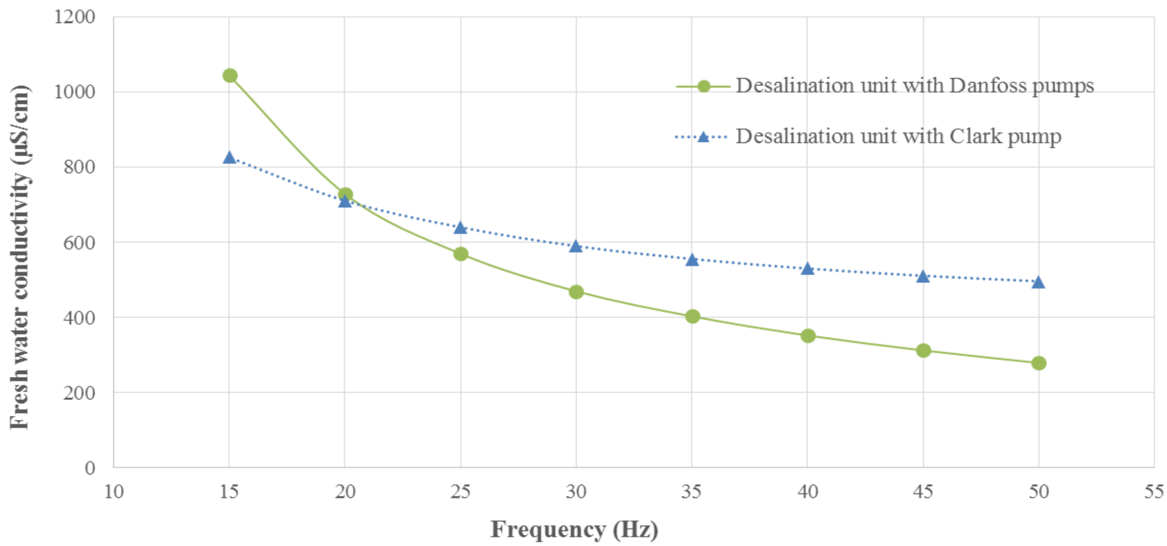

Figure 5: Fresh water quality as a function of the frequency of the motor.

3.5 Specific energy consumption

The specific energy consumption was calculated with equation Eq. 1.

$$S_{EC} = \frac{E_m}{Q_p} \qquad \text{(Eq. 1)}$$

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, indicated in Figure 6, is lower when both desalination units are operating in part load conditions. The lowest and the highest operating point can be defined by taking into consideration that the water needs to be safe for drinking. Thus there is an operation window for each desalination unit which ranges from approximately 25 Hz to 60 Hz (Figure 6), which correspond to a set membrane inlet pressures from 49 bar up to 67 bar for the Danfoss desalination unit and from 40 to 57 bar for the Clark desalination unit (see Figure 3). For this operating window, the specific energy consumption is lower than 6.6 kWh/m^3 in both desalination unit and the quality of desalinated water is drinkable (< 650 μS/cm) (see Figure 5). It is clear that the specific energy consumption values of the Danfoss desalination unit are lower comparing them to the corresponding values of the Clark desalination unit due to the fact that the energy consumption of the Danfoss's motor is low, with a power factor of 0.79 while the energy consumption of the feed water of the Clark desalination unit is high with a power factor of 0.58.

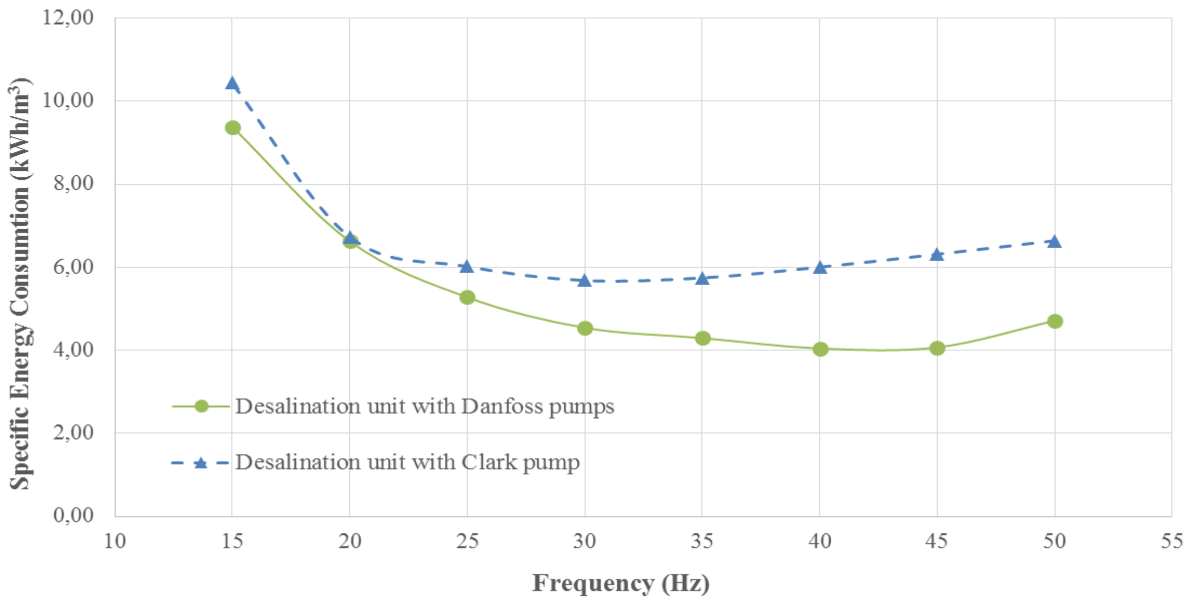

Figure 6: Specific Energy Consumption.

4 Conclusions

The conclusions 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 renewable energy systems as photovoltaics and wind turbines.

- Small – scale SWRO desalination units combined with energy recovery devices can decrease dramatically the specific energy consumption of the SWRO desalination unit.
- During the operation of each SWRO desalination units in part load conditions an operating window is identified approximately 25 Hz to 60 Hz (which corresponds to a set membrane inlet pressure of 49 bar to 67 bar for the Danfoss desalination unit and 40 bar to 57 bar for the Clark desalination unit) where the specific energy consumption is lower than 6.6 kWh/m^3 and the average quality of the desalinated water is within the limits of WHO (< 650 μS/cm).
- The comparison between the operating windows of both SWRO desalination units showed that the operating window of the Danfoss desalination unit is lower than this of the Clark desalination unit due to the fact that the energy consumption of the Danfoss's motor is low due to the power factor of 0.79 while the energy consumption of the feed water of the Clark desalination unit is high due to the power factor of 0.58.

5 Symbols

S_{EC} : Specific energy consumption (kWh/m^3)

E_m : Energy consumed by the feed water motor (kWh)

Q_p : Fresh water production (m^3)

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