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Variable renewable energy sources for powering reverse osmosis desalination, with a case study of wave powered desalination for Kilifi, Kenya

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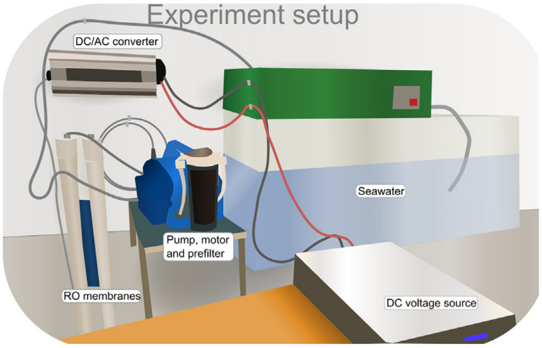
GRAPHICAL ABSTRACT



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ABSTRACT

An analysis of reverse osmosis powered by ocean wave power is provided. A commercially available desalination system is connected via a DC/AC converter to a variable DC source and the input voltage is altered to emulate the response of a renewable energy system. Specifically, wave data from Kilifi in Kenya during 2015 is used. The wave resource variations provide variations in estimated power output from a wave energy converter, as well as in estimated freshwater production from a wave powered desalination system. Up to three wave energy converters for desalination are investigated for Kilifi. Also, a hybrid system including solar and wave power is proposed. The experiments show that reverse osmosis desalination systems can function at power levels below the rated values, but with lower freshwater flowrates. It is concluded that wave power, or wave power combined with PV systems, may be considered as power sources for desalination, with or without battery storage.

1. Introduction

One of the greatest challenges with desalination is to reduce the amount of fossil fuels to power the processes. When powering a reverse osmosis (RO) desalination plant (DP) with renewable energy sources (RES), the intermittent nature of the energy sources can cause pressure fluctuations across the RO membranes. Such fluctuations may potentially decrease the lifetime of the system, increase fouling and lower the actual water production etc. [1]. A recent experimental study investigated intermittency and membrane fouling [2]. In order to

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generate a stable power level from the RES for the RO process, (costly) energy storage systems may be necessary [2]. The increased costs as well as environmental aspects involved when including batteries for solar and wind powered desalination were previously highlighted [3]. The technical problems with RES variability are not just addressed for desalination purposes; grid-connection of RES comes with several challenges which have been studied in recent years, with systems including e.g. battery storage, super capacitors or fly wheels [4]. Specific energy consumptions from different parts of common desalination technologies have been studied [5], highlighting for example problems regarding DPs powered by RES; finding suitable locations for the DP and RES power plants, matching electricity production from the RES to DP demand, handling intermittency as well as legal, economic and environmental aspects. Nonetheless, despite all the challenges, there are many possible benefits in designing small-scale desalination systems powered off-grid by RES. Ensuring access to clean drinkable water is highly important, and it has been estimated that around 4 billion people globally experiences water scarcity parts of the year [6]. In Kilifi in Kenya, there is a lack of freshwater, and the region is in focus of this study. Due to its location by the ocean, there are opportunities to utilize both desalination and wave power. This project is related to for example a previous collaboration on wave powered desalination in Kilifi [7].

Marine energy converters are not commercialized much yet but could be interesting future alternatives to fossil fuels or other RES for desalination. Both wave energy converters and desalination systems use the ocean (saline water and waves), the full system can function off-grid, could be adapted to a local electricity- or water demand, small systems could be beneficial for disaster resilience, and generally, wave powered desalination could be used to produce freshwater in remote coastal areas or on islands. The main aim of this paper is to take initial steps towards including more marine RES, here ocean wave power, for powering RO desalination systems. It investigates power fluctuations from wave power and over- and undersupply for RO desalination systems powered off-grid. It includes initial experiments on a test bench and a case study on wave powered desalination for Kilifi, Kenya. Therefore, the objective of the paper is to investigate and estimate freshwater production from a desalination plant in Kilifi, if the system is powered by wave power or. The research question of the paper is: What would the freshwater production from a desalination plant be, if it is located in Kilifi and powered (indirectly) by wave power, or possibly powered by a hybrid system including solar- and wave power? The overall methodology (i.e. system model) used is experiments with a small-scale desalination system, combined with calculations based on resource data for Kilifi, and estimations on power output from renewable energy converter systems. The paper is structured as follows; first, a background to the work on variable powering of desalination systems is given. Secondly, data on the wave resource in Kilifi, Kenya, during 2015 is utilized to estimate power output from energy converters. Thereafter, the experimental setup is described. Finally, results from experiments and simulations are presented and discussed.

2. Background to RES powering RO desalination

Most of the work performed in RES powered desalination involves variable solar- and wind power. The occurrences of ocean waves, marine currents or tides change in an intermittent manner, but on different timescales and in different amplitude than for solar and wind. The variability of different kinds of RES (solar, wind, wave, tide) was reviewed in Widén et al. [8]. Due to its difference in variability, ocean resources could be interesting for desalination. In Fig. 1, the significant wave height [m] at Islandsberg (Swedish west coast) is presented for 31 March 2020. For the same day, Fig. 2 shows the wind speed [m/s] for Marsta, Sweden, at ten meters height. Furthermore, Fig. 3 shows global irradiance [W/m^2] in Marsta for 31 March 2020. Figs. 1–3 are included to represent how the resources wave, wind and solar can vary over a day (here in Sweden during 31 March 2020), noting that (possibly) typical differences in resource variability over a day could be interesting to utilize when powering desalination plants with one or several RES. Whereas PV do not produce electricity nighttime, there is an opportunity to produce electricity all hours with for example wave energy converters (WECs). A study on wave, wind and solar also mentions the differences in variability of the resources, concluding that wave power is more easily forecasted than the other sources [9].

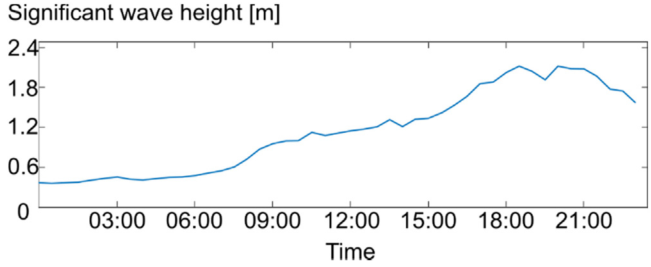

Fig. 1. Significant wave height from wave measuring buoy in Islandsberg, Sweden, for the day 31.03.2020, remade with permission. https://www.teknik.uu.se/elektricitetslara/forskningsomraden/vagkraft/lysekil/ [Accessed: 2020-04-21].

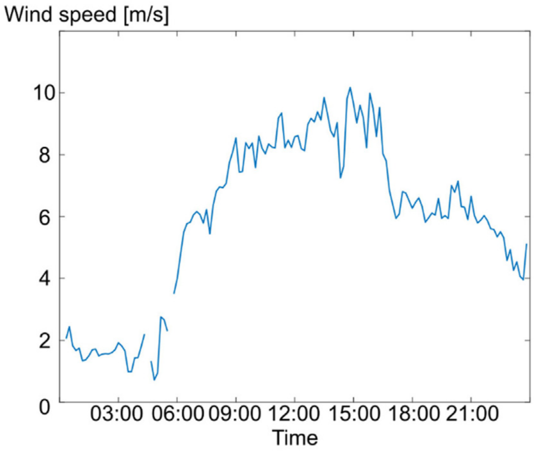

Fig. 2. Wind speed [m/s] at 10 m height measured in Marsta, Sweden, over the day, 31.03.2020. http://celsius.met.uu.se/?pageid=12&meny=7 [Accessed: 2020-04-21].

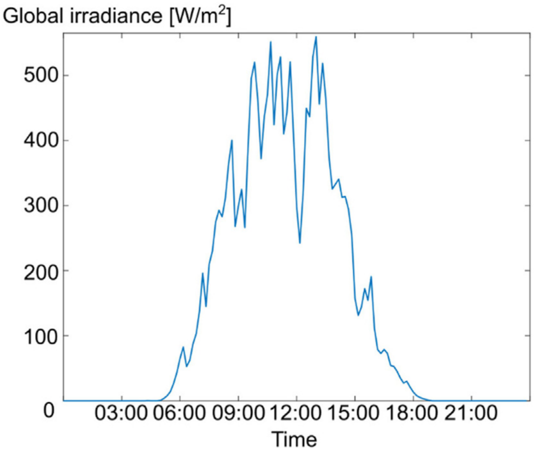

Fig. 3. Global irradiance [W/m^2] measured in Marsta, for the day 31.03.2020.

To date, several studies have investigated solar powered desalination. Variations occur with day and night, as well as with incoming clouds. A PV powered RO desalination system was modelled in Freire-

Gormaly and Bilton [1], with a focus on intermittent operation (such as shut down during nights) and the associated fouling of the RO membranes. In Freire-Gormaly and Bilton [2], the authors describe a lack of experimental work related to membrane fouling under intermittent power. Therefore, they study fouling for a small solar powered RO system in Mexico with experiments, concluding that cleaning the membranes with permeate water before a longer shutdown was good for the membranes. In a recent study, a techno-economic analysis of a PV-RO system was presented [10]. The authors concluded that these systems can be economically feasible.

Previous research has established that wind power can be utilized for desalination. A wind powered RO system for a variable load, with hourly differences in flows and pressures according to the available wind resource, and to strategically store water, was investigated in Loutatudou et al. [11]. Running a brackish water reverse osmosis (BWRO) system with fluctuating power at different levels, possibly resulting from fluctuations of wind power without energy storage, was investigated in Park et al. [12]. Three different cases were primarily analyzed [12]; (i) constant power for 20 min from 60 W to 300 W, (ii) different ranges of oscillating power and (iii) power variations with periods of no power at all. In this study, it was concluded that an intermittent RES, such as wind power, could safely and directly power the RO process. Trouble may however occur if there is no power available at all, rather than if there are fluctuating power levels – suggesting the use of energy storage to cover up for down-periods. A varying pressure across the RO membranes (cyclic operation) was applied and investigated in Al-Bastak and Abbas [13]. Furthermore, variable operation of seawater reverse osmosis (SWRO) systems adapted for wind power was investigated with simulations in Pohl et al. [14].

Hybrid systems have also been considered for desalination. A combined system with geothermal, solar and ocean energy thermal energy converters were proposed in Azhar et al. [15] not only for desalination purposes, but also electricity generation, cooling and heating. A system consisting of both solar and a diesel generator was investigated in Wu et al. [16]. An overview of a hybrid system of solar and wind in three different cases, in combination with battery storage, for RO desalination in London was provided in Li et al. [17].

Many studies on ocean energy have been conducted over the past years. A rather recent review paper on the topic, especially highlighting areas that could benefit from further research, is Uihlein and Magagna [18]. A few studies have investigated ocean energy for powering of desalination systems [19–21], for example projects such as CETO Freshwater, Delbuoy and the oscillating water column in Vizhinjam, India. Wave powered desalination can be combined directly, where the wave power system is used directly to pressurize the saline water for the RO process, or indirectly, where the WEC is first used to generate electricity which can then be used to power the DP [20]. Previous research in this field included combined models of wave power and desalination, for example discussing how to handle pressure variations with a pressure accumulator and a pressure-relief valve [22]. However, the amount of research on ocean energy for desalination is small in comparison to the research published on wind or solar for desalination. In comparison to small-scale wind- or solar powered desalination, some main challenges with marine RES for desalination are for example: the harsh and corrosive marine environment, complexity in installation and maintenance, new and not fully commercialized technologies, uncertainty on for example system cost and potential effects on marine life. Some main opportunities of small-scale marine RES for desalination, in comparison to for example wind- and solar powered systems, are for example: the co-location of ocean waves and seawater, that many people live by the coasts where the systems are used, the difference in intermittency and predictability, and the opportunity to utilize local marine resources.

A technical overview of an RO system powered by solar panels (DC source) or wind, current or wave power generators (AC source) are shown in Fig. 4, remade with inspiration from [17], with batteries included to stabilize the power level. The RO system utilizes AC and the most important output from the system is the freshwater. There is also a salty residue (brine) from the desalination plant to manage.

Drinkable water has salinity, i.e. total dissolved solids (TDS), of about 500 ppm. The salinity of brackish water varies from 1000 ppm up to less than 35,000 ppm. The salinity of seawater is at least around 35,000 ppm. There are several different desalination technologies available [23]. The energy demand of BWRO is about 1–1.5 kWh/m^3 and for SWRO it is about 2.5–4 kWh/m^3 [24]. The energy demand varies for example with the size of the desalination plant and with the use of energy recovery, where a smaller desalination plant without energy recovery may result in a higher energy demand than a larger plant with energy recovery. As highlighted in Shemer and Semiat [25], the price of a bottle of freshwater varies significantly across the globe, and there are countries where tap water is for free. Also, the electricity price varies with locations and over time. The price of freshwater from a SWRO system also varies for different plants (and locations) as indicated for example in Shahzad et al. [23].

3. Case study Kilifi, Kenya, and presentation of resource data

In the following, a case study of wave powered desalination for Kilifi, Kenya, is considered. The system model and methodology is summarized in the following steps: i) purchased data on the wave- and solar resource in Kilifi, Kenya, during 2015, is utilized, ii) the power output from wave energy conversion for Kilifi is estimated based on previous studies of the WEC system and the power output from a small solar PV system in Kilifi is estimated, iii) experiments on a small-scale desalination system is performed to estimate how much freshwater that could be generated for different power levels, iv) the calculations, estimations and experiments are combined to estimate potential freshwater production for Kilifi, Kenya, during 2015, from a wave power system, and/or hybrid system including a PV system, which indirectly powers a desalination plant. All calculations are done in MATLAB.[1] There are several assumptions and limitations with the proposed system model, such limitations of measurement equipment, limitations in resource data, rough estimation of power output from the energy converters etc. These assumptions and rough estimation have impact on the results, suggesting that more in-depth studies could be interesting in the future. The site Kilifi is chosen due to freshwater shortage and as it is a remote location with limited access to an electric grid, but with available marine RES and seawater to desalinate. Also, the site was included in previous research collaboration with Strathmore University[2] in Kenya. In Kenya, 59% of the households in 2017 had safe access to drinkable water, 29% to basic sanitation services and 25% to basic hygiene services.[3] About 64% of the population in Kenya had access to electricity in 2017.[4] Kilifi is a coastal community facing the Wester Indian Ocean and the Kilifi county had a population of 1,466,856 people in 2017.[5] Solar, wind and wave resources vary with season etc. and rough estimations are utilized and presented in the following analysis. As presented and estimated in the SolarGIS Atlas,[6] a PV system for a small building in Kilifi, with installed capacity of 2 kW and a tilting angle of the panels of 4 degrees, could roughly, typically produce from 0 to 1.2 kW. Resource data from Solargis is used, which shows for example the global horizontal irradiance (GHI) [W/m^2] for the day 31 December 2015 for Kilifi, Kenya, with 15 min resolution (solar resource

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[1] https://se.mathworks.com/products/matlab.html [Accessed: 2020-07-03].

[2] https://www.strathmore.edu/ [Accessed; 2020-04-20].

[3] https://washdata.org/data/household#!/ [Accessed: 2020-04-09].

[4] https://data.worldbank.org/indicator/eg.elc.accs.zs?name_desc = false [Accessed: 2020-04-09].

[5] https://www.kilifi.go.ke/content.php?com = 2&com2 = 4&com3 = 43&com4 = #.Xo7n225uJu1 [Accessed: 2020-04-09].

[6] https://globalsolaratlas.info/detail?s = -3.66667,39.75&m = site&c = -3.666585,39.749565,11&pv = small,0,4,2 [Accessed: 2020-04-08].

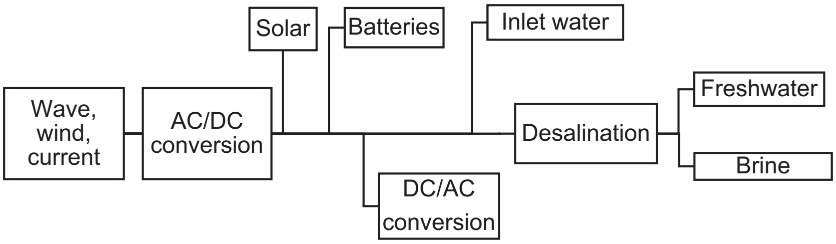

Fig. 4. A sketch on a desalination system powered by different renewable energy sources, remade with inspiration from [17].

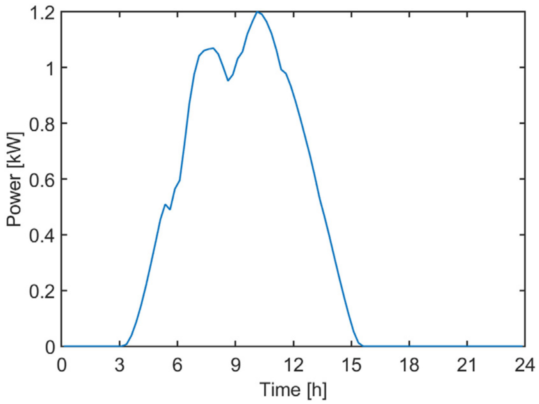

Fig. 5. Estimation of power production from a small PV system in Kilifi, Kenya, during 31 December 2015. Estimations based on solar resource data from © Solargis.

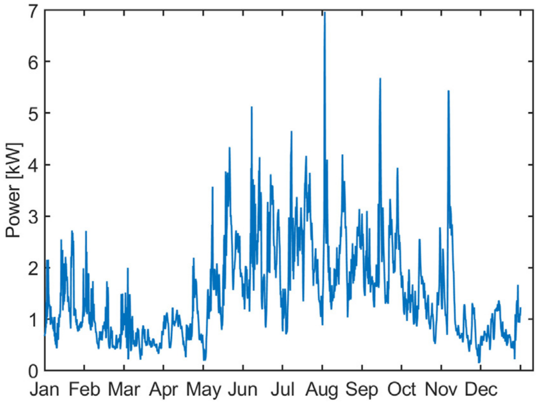

Fig. 6. Output power [kW] from one WEC in Kilifi, representing the full year 2015, assuming power absorption of 24% from the available wave resource.

data © Solargis). Assuming that the maximum output power from a small PV system at the site over the day is 1.2 kW, power output over the day during 31 December 2015 is estimated and shown in Fig. 5. Note that this is a very rough estimation of power output from a small-scale PV system and considerations on for example temperature effects of power production have not been included.

The wave resource for a site in Kilifi, Kenya, during the period Jan. 1997 to Dec. 2015 with 6-hour resolution, was provided by Fugro[7] (doc. 162030-1-R0) and reanalyzed in Francisco et al. [7]. There are noticeable daily and seasonal variations in wave power resource, as well as variations in wave directions. As such, any suggested WEC system would vary in power output. With a theoretical background described for example in Pecher and Koefoed [26], the wave power resource [kW/m] is estimated as

$$P_w \cong 0.5 H_s^2 T_e, \tag{1}$$

for significant wave height H_s [m] and mean wave energy period T_e [s]. The annual mean wave power resource by Kilifi was estimated to 7 kW/m in Francisco et al. [7]. This is a mild wave climate in comparison to for example the Wave Hub test site in UK [27]. During the years 1988 to 2010, the monthly average on Wave Hub, UK, varied from about 15 kW/m to over 100 kW/m [27]. In the following, wave resource data from Fugro for the year 2015 for Kilifi, Kenya has been utilized. This year was chosen as it is the most recent year in the Fugro dataset, noting that there may be significant seasonal differences in the local solar- or wave resources. A power absorption of 24% for the WEC is assumed [28] (here the WEC is a point absorbing buoy, 3 m in diameter, connected with a wire to a direct-driven linear generator on the seabed). The power output from one WEC in Kilifi, Kenya, is presented in Fig. 6 (one year, 2015) and Fig. 7 (one month, December 2015, and almost one day, 31 December 2015). Note that the power absorption may vary with the suggested type and design of WEC and control of the WEC [29,30], as well as seasonally. Furthermore, some WEC systems are designed to be combined in larger parks, increasing the total power output and perhaps decreasing (i.e. smoothing out) its variability. A maximum power output of 7 kW from one of the proposed WEC could be expected during 2015, but lower power values are expected more often. The output power is estimated to be mainly around 1 to 4 kW per unit. The WEC could be designed to withstand high power peaks, in comparison to the average output power [31]. The power output for the year including two and three WECs, are estimated to roughly contribute with two respectively three times the output power from one WEC over the year. Mean estimated power output from one WEC for 2015 would be around 1.5 kW, for two WECs 3 kW, and for three WECs 4.5 kW.

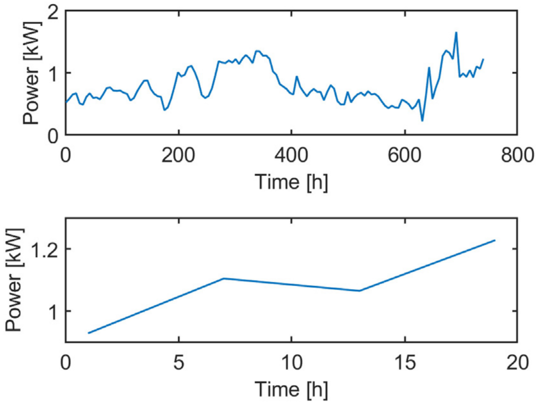

Fig. 7. Output power [kW] from one WEC in Kilifi over hours, representing a month (December 2015) and about a day (31 December 2015), assuming power absorption of 24% from the available wave resource.

4. Experiments

4.1. Experimental setup

The section below describes experimental work on a small off-the-

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[7] https://www.fugro.com/ [Accessed: 2020-07-03].

shelf portable desalination system. It was purchased from an existing supplier, Rainman Desalination,[8] with RO membranes from a commonly used brand, Lenntech.[9] The system was chosen based on cost, size, purpose etc. Specifics on the system are shown in Table 1. An overview of the experimental system is shown in Fig. 8.

The testbench RO system consists of *(i)* a pressure supply unit (PSU) and *(ii)* the RO system [32]. In more detail; *(i)* the PSU consists of an intake hose for the saline inlet water, a pre-filter system, a high-pressure pump with a power cord and a power switch on. *(ii)* The RO system consists of the two series connected RO membranes in two pressure vessels, one pressure gauge showing the pressure level in psi and bar, three different hoses: a black hose for the high pressure water, a white hose for the clean product water and a green hose for the saline brine. The rated power values are 2 kW peak and 1.6 kW continuously from an AC source [32]. The optimum pressure, in manual, is 55 bar, 800 psi, for seawater, generating about 2.3 l each minute. To desalinate brackish water, only 13 bar, 200 psi, may be used. The system data is summarized in Table 1. There are several risks to avoid highlighted in the manual, such as; *(i)* water with chlorine (such as tap water) cannot be used as inlet water. *(ii)* The pressure should not increase with more than 20 bar, 300 psi, each minute. *(iii)* The pressure should not be above 58 bar, 850 psi (there is a relief valve acting if too high pressure). The experimental setup consists of an aquarium with blended saltwater to 35 ppt (to represent seawater), a variable DC voltage source with two multimeters for current- and voltage measurements, a DC-to-AC converter, a Rainman desalination system including motor, pump and the two RO membranes, a flow measurement setup and two different salinity- and temperature measurement systems. The measurement systems only give accurate values during certain ranges, for example the flow measurement setup only works appropriately for water flows above one liter per minute. The experimental setup is shown in the photo in Fig. 9.

4.2. Results from experiments

The experiments with the desalination setup included variations with the manual gauge to change the pressure or the system from 0 to 1000 psi (0 to about 6,894,760 Pa). The salinity and temperature of the inlet water, and salinity of clean produced water, was measured with the salinity meters (TDS meter) for the accurate range. The clean water flowrate from the desalination system was measured with the flow meter. Note that there are uncertainties in the measurements to due to for example the limitations of the measuring devices. For a constant voltage of 12 V, and an inlet solution with constantly about 35 ppt and 20 °C, the results are provided in Figs. 10 to 12. Fig. 10 shows that the production of freshwater starts at a certain pressure, above about 2 MPa, and that the salinity of the produced freshwater decreases much, from almost 200 ppm to about 60 ppm, as the pressure increases. This is the case up to about 6 MPa where the salinity of the clean water increases again. It is noted that the salinity is lower than the suggested level of max. 500 ppm for drinkable water. In Fig. 11, the increase of the current is almost linear, from about 70 A to about 160 A, when increasing the pressure up to 7 MPa. Fig. 12 shows that the flowrate of the clean water increases, up to over 3 l/min, for increasing power [W]; the flowrate decreases for the highest power values.

5. Estimated amount of freshwater produced from desalination system in Kilifi, Kenya

Estimations of freshwater production [liter/min], from a SWRO system powered by a WEC for Kilifi, Kenya, during a day (31 December 2015) and a month (December 2015) are shown in Figs. 13 and 14, respectively.

Table 1
Data from manual on the desalination system from Rainman desalination [32].

Property	Value
Pressure	Brackish water: 13 bar, 200 psi. Seawater: 55 bar, 800 psi (from manual); acceptable pressure 51 to 58 bar, 750 to 850 psi.
Permeate flow	140 l per hour
Membrane	Twin 40-inch membranes, 101.6 cm
Recommended power supply	AC, 2 kW peak, 1.6 kW continuously

With one WEC over one year, 2015, in Kilifi, the power overproduction from the system (in relation to the power levels useful for the desalination system in the experiments), is estimated (i.e. here, when more electricity is produced from the WEC than the highest value utilized in the experiments) and presented for 2015 in Kilifi in Fig. 15.

In the following, it is assumed that when the power production from the WEC is higher than the power values tested in the experiments, the resulting flowrate would result from the highest power use (i.e. 1908 W resulting in 2.85 l/min, noting that a higher water production rate was achieved for lower power level). The water production from the desalination plant powered by one WEC in Kilifi over 2015 is shown in Fig. 16. If instead two or three WECs were used for the desalination plant, assuming roughly no time shift or variability in the power output from the WECs, the estimated freshwater production is seen in Figs. 17 and 18.

In the following, it is assumed that a solar PV system is connected to the RO system. The PV system is assumed to generate the power for one day (31 December 2015) as shown in Fig. 5. Note that this estimation is very rough. Based on the data from the experiments, this would generate the freshwater production for that day as seen in Fig. 19. Now combining one PV system and one WEC in a hybrid system, this could result in the power output [kW] for a day (31 December 2015) as shown in Fig. 20 (i.e. this is a combination of data shown in Figs. 5 and 7). The water production during this day for the hybrid system is presented in Fig. 21. The total estimated freshwater production from different system configurations are summarized in Table 2 (estimated using MATLAB-function: *trapz*).

6. Discussion

The production from a wave powered desalination (WEC/DES) plant can be considered for four different states: (i) rated supply, (ii) under supply, (iii) over supply and (iv) system downtime. Which power levels each state represents depends on the overall design of the WEC/DES system. The most preferred state is (i) rated supply of power and freshwater, whereas (iv) system downtime is the least preferred state for a WEC/DES system. (iv) System downtime could occur when the power output from the WEC is either too high or too low to ensure that the RO system provides any freshwater. Also, it occurs when the system is shut down for other purposes, such as maintenance. This state (iv) could be avoided by increasing the energy supply with additional WEC units, other energy converters (hybrid system) or energy storage. Such solutions could be used to balance the system and to ensure that it more often provides the rated power and rated amount of freshwater. A hybrid system including both PV and WEC for desalination in proposed in this study. The results in Table 2 shows that this configuration leads to a much higher daily freshwater production (at least for the investigated day 31 December 2015) than the water production from solely solar- or wave powered desalination. In the results, it is also noted that increasing the amount of WECs increases and stabilizes the power- and freshwater production. However, this results in a higher cost for the full system and increased overproduction of power. Other hybrid systems with wind, solar, wave, marine current energy converters or tidal energy converters could be combined or investigated in future research

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[8] https://www.rainmandesal.com/ [Accessed: 2019-10-08].

[9] https://www.lenntech.com/ [Accessed: 2019-10-08].

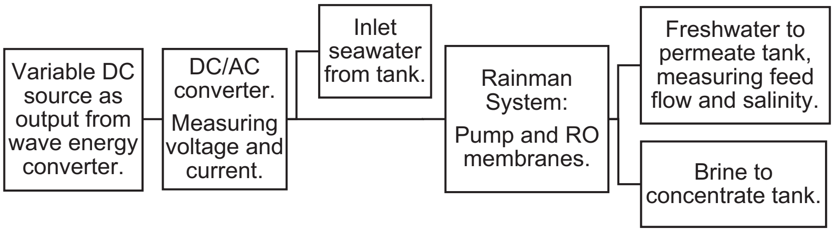

Fig. 8. An overview of the experimental setup, including e.g. a variable DC source, a DC-to-AC converter and the Rainman desalination system.

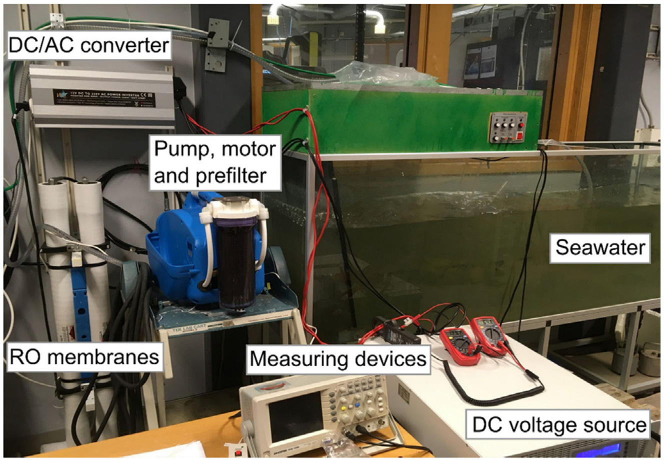

Fig. 9. Photo of the experimental setup, including aquarium with saltwater (35 ppt), measuring systems, desalination system etc.

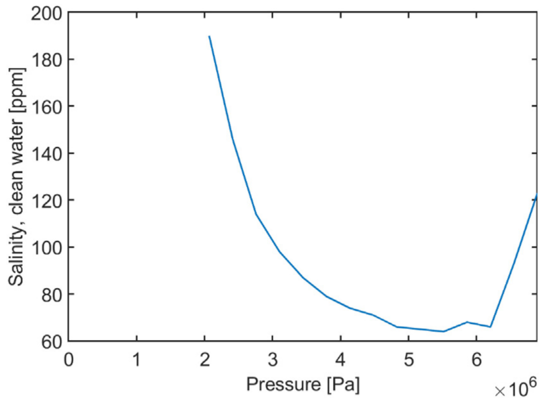

Fig. 10. Experiments with Rainman RO desalination system. For different pressures [Pa] and salinity [ppm] of the produced clean water.

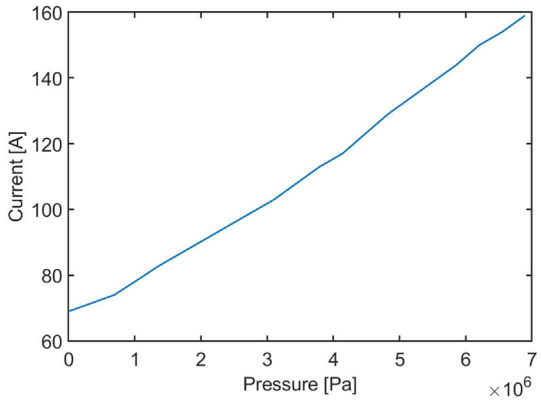

Fig. 11. Experiments with Rainman RO desalination system. For different pressures [Pa] and current [A] of the DC power supply when used for 12 V.

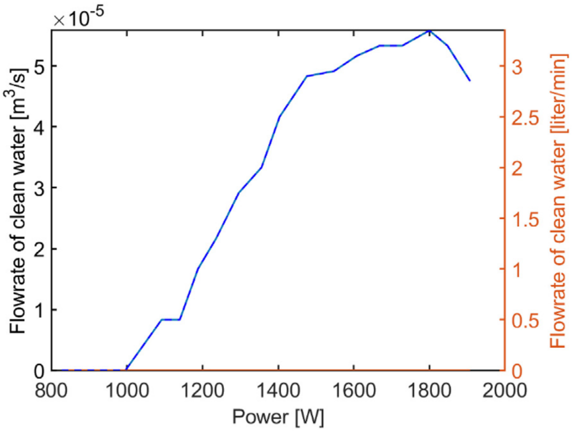

Fig. 12. Experiments with Rainman RO desalination system. Flowrate of clean water in [m^3/s] and [liter/min] is shown for different power levels [W].

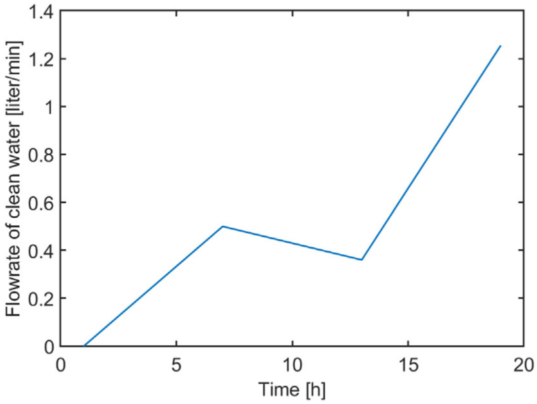

Fig. 13. Flowrate [liter/min] estimated for a RO desalination system connected to one WEC in Kilifi, Kenya, over about a day, 31 December 2015.

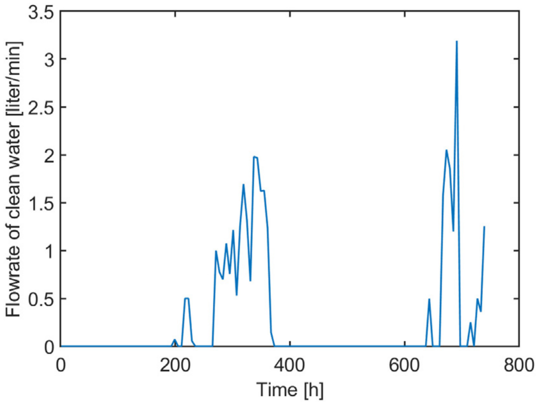

Fig. 14. Flowrate [liter/min] estimated for a RO desalination system connected to one WEC in Kilifi, Kenya, over a month, December 2015.

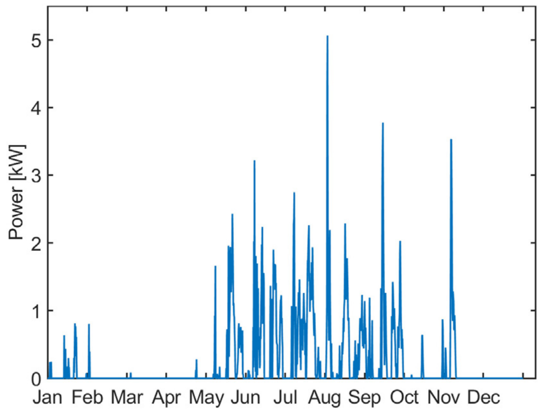

Fig. 15. Power overproduction [kW] from one WEC over the year 2015 in Kilifi, in relation to the need of the desalination system used in the experiments.

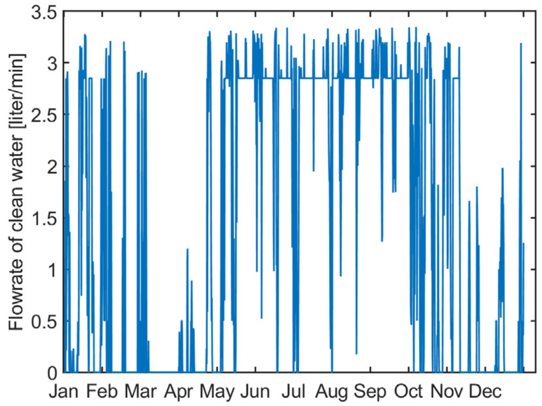

Fig. 16. Flow rate of clean water [liter/min] from desalination powered by one WEC in Kilifi, Kenya, during 2015.

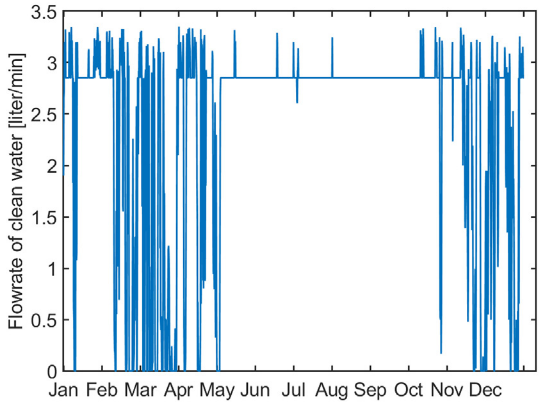

Fig. 17. Flow rate of clean water [liter/min] from desalination powered by two WECs in Kilifi, Kenya, during 2015.

for desalination. Especially as the available resources varies locally and the resource variability changes on different timescales. Utilizing freshwater storage and including fouling prevention (e.g. flushing the membranes with cleaning water) may be considered during periods of (iv) downtime. Moreover, the same strategies may be used during (ii) under supply. During periods of (iii) over supply, the power may be supplied to an electric grid, to other specific functions, used for energy storage or used to provide more water to store in a freshwater storage tank. Mobile phones or electric vehicles could be charged during over supply. There is a significant overproduction in electricity in comparison to the need of the experiment desalination system, when utilizing one WEC for desalination, as shown in Fig. 15. This suggests that the power produced could be used for other purposes as well.

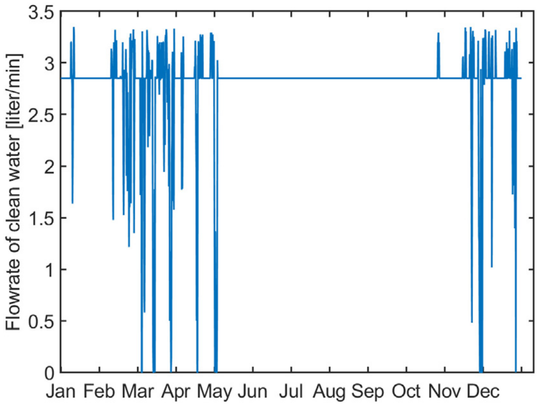

Fig. 18. Flow rate of clean water [liter/min] from desalination powered by three WECs in Kilifi, Kenya, during 2015.

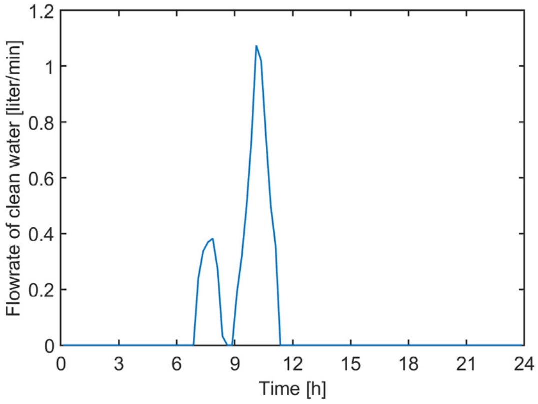

Fig. 19. Flowrate of clean water over one day (31 December 2015) estimated for a small-scale PV powered desalination system in Kilifi.

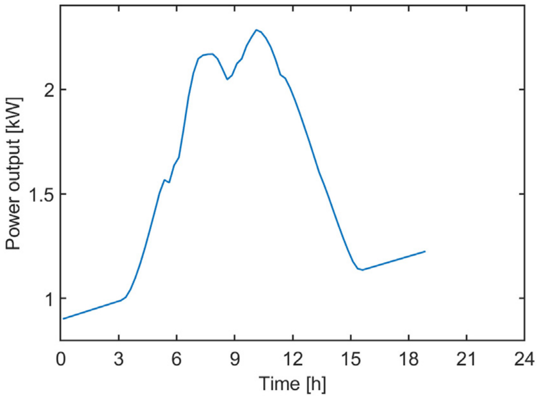

Fig. 20. Power production estimated for hybrid system for about one day, 31 December 2015, in Kilifi, Kenya, including one PV system and one WEC system.

Both WEC systems and desalination systems should be designed and scaled in size to match the local wave climate, freshwater need etc. Looking at Fig. 11, Rainman RO system provides freshwater from about 85 A and 12 V, resulting in 1020 W. This is lower than the suggested rated power value of 1.6 kW shown in Table 1. This is also in the range of 1 to 4 kW estimated to be produced often by the WEC for the Kilifi site, according to Fig. 6. This means that periods where the WEC system provides lower output power (i.e. state (ii)) may also be useful for desalination. However, running a desalination plant below its rated values

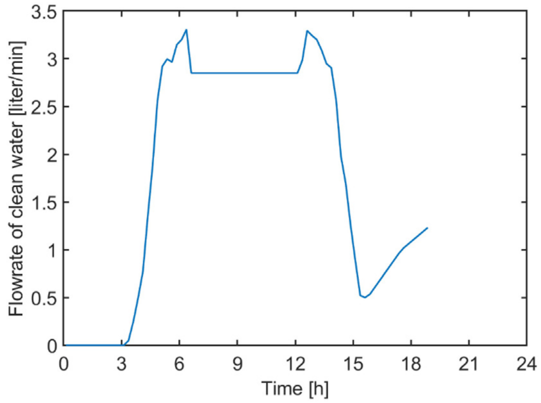

Fig. 21. Flowrate [liter/min] over about one day, 31 December 2015, from hybrid small-scale system including one PV system and one WEC connected to a desalination system.

Table 2
Estimated total freshwater production from different system configurations for powering of a small-scale SWRO desalination system in Kilifi, Kenya.

System description for powering the RO desalination in Kilifi	Time	Estimated freshwater production [liter]
One WEC system	About one day, 31 Dec. 2015	536
One PV system	31 Dec. 2015	106
One WEC and one PV system	About one day, 31 Dec. 2015	2009
One WEC system	Dec. 2015	11,811
One WEC system	About one year, 2015, (8755 h)	780,560
Two WEC systems	About one year, 2015, (8755 h)	1,273,600
Three WEC systems	About one year, 2015, (8755 h)	1,454,100

may result in fouling, according to literature, as well as a lower and insecure freshwater supply. It was noted that a dirty pre-filter had a great impact on the power demand from the test bench desalination system; this increased the current and fluctuations. Therefore, to decrease the power demand of the system, it is interesting to look at the pre-filtering. Power output from a WEC depends on the overall design and available ocean waves etc. The value of a 24% power absorption may be too low, considering the currently ongoing design development of systems such as point absorbers, oscillating water columns and overtopping systems. As WECs are still in a pre-commercial state, the actual electricity produced from future largescale systems or parks are not fully understood yet. The feasibility of desalinated water from wave powered RO depends on the local alternative price for freshwater, electricity etc. Also, this study includes several limitations: estimations of parameters and resource variability, simulations instead of full experiments etc. More research is needed to design RO desalination systems fully powered by marine RES, and wave energy could be more in focus in discussions on RES powered sustainable desalination.

7. Conclusions

Wave data from Kilifi, Kenya, in 2015 has been presented along with experimental data on a commercial RO system, discussing the opportunity of wave powered RO systems. It is concluded that the power availability of the ocean waves for WECs in Kilifi, Kenya, varies significantly in 2015, but on different timescales than for solar and wind. From this, power output from a WEC is estimated (max. 7 kW here) and it would be enough to power an RO system of appropriate size. Experiments on a commercial RO system show that it can provide freshwater from power values other than the rated (1.6 kW), suggesting that variable RES such as ocean wave power can be considered. The downtime of a RES powered desalination system can be limited utilizing energy storage or additional energy converters. Also, a hybrid system including a WEC and a PV system for desalination was proposed. To implement wave powered desalination systems in full scale, more research is needed, especially since wave power is still in a pre-commercial state. More experimental work in the field could be valuable. These initial studies show that RO desalination powered by wave power could be interesting to study further.

Author statement

J.L. wrote most of the paper and performed the simulations. J.L. and D.S. did the experimental work. J.E., M.L. and C. B. supervised the work. All authors were part of discussing, planning, reviewing and editing of the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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