Desalination 435 (2018) 161–171

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Freshwater production from the motion of ocean waves – A review

Jennifer Leijon*, Cecilia Boström

Division of Electricity, Uppsala University, Box 534, 751 21 Uppsala, Sweden

A R T I C L E I N F O

Keywords:
Wave power
Desalination
Wave energy converter
Reverse osmosis
Freshwater
Water scarcity

A B S T R A C T

Freshwater scarcity and insufficient sanitation are global urgent problems, affecting billions of people. In this review paper, the process of desalination powered by wave power has been investigated as a potential sustainable solution to water shortage. The different desalination techniques suitable for this type of combined system, i.e. reverse osmosis, electrodialysis and mechanical vapor compression, have been outlined, as well as the different wave energy converters possible to power the desalination process, i.e. oscillating water columns, oscillating bodies (wave activated bodies) and overtopping systems. Some necessary considerations for this type of project are identified. The different wave power/desalination projects and how they have proceeded are presented. The most common design of a wave energy and desalination system includes a wave activated body to pressurize seawater; the seawater flows through a reverse osmosis membrane, resulting in freshwater. Some successful (freshwater producing) wave energy/desalination projects were identified: Delbuoy, the oscillating water column in Vizhinjam, CETO Freshwater, SAROS and Odyssée. It is concluded that wave power and desalination can be combined in a sustainable and autonomous system, generating freshwater from the ocean waves. However, questions regarding cost of produced water, variations in power production due to intermittency and environmental effects still remain.

1. Introduction

Water scarcity is a severe global problem; billions of people experience water scarcity at least parts of the year [1]. Water shortage is common at remote rural areas, for example on islands [2]. Industries and energy production may depend on a vast amount of clean water [3]. Access to clean water is at the heart of sustainable development - inducing social, economic and environmental growth [3]. The United Nation's goal for access to freshwater, described in the 2030 Agenda for Sustainable Development, is to “ensure availability and sustainable management of water and sanitation for all” [4]. Desalination can play a part in addressing the issue of water scarcity. The desalination process, where clean potable water is produced from sea or brackish water, is performed with the use of membranes or through a thermal process [5]. One way to secure a sustainable process is to use a renewable energy source to power the desalination plant. The use of renewable energy sources to power a desalination plant and cover a freshwater demand has several benefits in comparison to the use of fossil fuels or to transport freshwater by trucks or ships. Renewable energy sources are more environment-friendly, and the prices can be lower depending on the design of the energy converter [6,7]. However, the disadvantages of a desalination plant powered by renewables are the intermittency and sometimes the cost of the system [6,7]. One example of a renewable energy source that can be used for desalination is the ocean waves [8,9].

The motion of the ocean waves can be harnessed to produce freshwater, using a combined wave power and desalination system. If the system is autonomous, or stand-alone, it works without an external electric grid, which would be beneficial since many locations in need of freshwater have unreliable electric grids. Mainly, wave power can drive the desalination process in two ways: indirectly or directly. The power in the ocean waves can be converted to electricity to power the desalination plant (indirectly), or it can convert the movement into pressure and thereby directly run the process. The wave power-desalination process can roughly be divided into four different blocks to study further: the *ocean* is the source of energy and also the source for the final product; the *wave power system* converts the energy of the ocean waves in a suitable way; the *desalination plant* and finally, the storage and distribution of *freshwater*.

The potential for using wave power as an energy source is huge; it has been estimated to 8000–80,000 TWh/year [10]. The high potential in combination with the proximity of the energy source and end product makes wave power a promising technique for powering desalination systems. To the best of our knowledge, it was more than a decade ago since wave powered desalination systems were last discussed in a review paper [8]. Recently, researchers have shown an increased

* Corresponding author.
E-mail addresses: jennifer.leijon@angstrom.uu.se (J. Leijon), cecilia.bostrom@angstrom.uu.se (C. Boström).

https://doi.org/10.1016/j.desal.2017.10.049
Received 30 June 2017; Received in revised form 28 September 2017; Accepted 26 October 2017
Available online 13 November 2017

interest in the field, due to the demand of reliable and sustainable freshwater sources and the development of well tested wave power technologies. The aim of this paper is to present a review on what has been done in this field before and highlight future areas that need to be studied further. This paper begins by giving a brief background to desalination systems mainly powered by renewable energy sources. It will then go on to describe some features of the waves and seawater, present different wave power concepts and different desalination technologies. A framework for categorization of these systems is suggested and thereafter, wave powered desalination systems from literature are described. Finally, the findings are summarized and conclusions are drawn.

1.1. Powering desalination systems

The desalination supply chain can be divided into four steps: intake of feed water and pretreatment, desalination process, water storage and water distribution [11,12]. It is important to find sustainable solutions to all steps of the supply chain, and the sustainability of desalination was discussed by Gude [13]. Although some cities are provided with drinkable freshwater from desalination plants, recent research shows that many citizens still prefer to buy bottled water, in spite of its additional cost [14]. As concluded by Fragkou and McEvoy, it is important to not only invest in the desalination plant itself, but also in the overall water system, decreasing local mistrust [14]. The size of desalination systems varies from small-scale devices to larger plants. One of the world's largest desalination plants is the Hadera plant in Israel, producing about 127 Mm^3 water each year [15]. In contrast, many remote areas and villages benefit from autonomous small-scale desalination plants, producing only one or a few cubic meters of freshwater daily [16], adapted in size to the need of the local population [17,18]. One of the main obstacles with desalination is the amount of energy needed to power the process [19,20]. In order to power a reverse osmosis process, about 2 kWh/m^3 is needed, but this value varies with the technical solutions [21,22].

The energy source suitable to power the desalination process depends on the available energy source as well as the seawater characteristics at the specific location [23]. The conventional energy source for desalination is fossil fuels [24]. Although many locations are well suited for renewable energy production, this is not always the energy source chosen when powering a desalination plant. For example, at the Canary Islands, over half of the total consumed water was produced from desalination and more than 90% of the primary energy consumption was produced from oil, transported by ships to the islands [25]. Some desalination plants are powered by nuclear energy [26] and comparisons of nuclear powered- and fossil fuel powered desalination plants have been published [27]. Other desalination processes are powered by a combination of different renewables and/or fossil fuels; this is called a hybrid system [28,29].

Considering a wind powered desalination plant, the variation of wind speed, leading to a variation in power output from the wind turbine, can have negative effects on membrane desalination processes, as well as the overall performance of the plant [6]. This can be solved with good technical solutions and energy storage. A reverse osmosis desalination plant which varies its energy consumption with the variation of the wind power powering the system has been suggested in [30]. Control systems have been proposed for desalination plants powered by solar and/or wind [31]. The price for desalinated water is an issue greatly affected by the price of the energy needed - but in the end, clean water, food and an overall sustainable future is an absolute necessity, reducing the importance of water cost [32].

As mentioned, renewable energy sources such as solar- and wind power have been combined with desalination [6,7,33]. Solar powered desalination is widely used and has been described in different review papers [34,35]. In the review on solar energy combined with desalination, provided by Sharon and Reddy, technologies such as the solar still and solar multi-stage flash desalination were described [36]. Focusing on solar power and geothermal power, Ghaffour et al. present an overview of some desalination systems powered by renewables [24]. It is concluded that these solutions are, so far, most feasible for autonomous systems in rural areas, but that its competitiveness for other desalinations plants increases as the cost of fossil fuels goes up [24]. Moreover, the environmental issues of fossil fuels also encourages the change to renewable energy sources [35].

There are several proposed systems combining renewables and desalination for a certain location and some examples are presented in the following. A system combining wind power, hydropower and desalination, to generate freshwater in St. Vincent, Cap Verde, was proposed and investigated by Segurado et al. [37], pointing out the importance of both working with water and energy in the same system to decrease water scarcity in remote areas. The control of a desalination plant in Kerkennah Island, Tunisia, powered by both wind and photovoltaics, was simulated [38]. A model describing the performance of a desalination plant and reservoir powered by wind power and hydropower for Taichung in Taiwan was suggested [22] and the optimal design of wind and solar (photovoltaics) powered autonomous desalination plants were investigated for Darvazan, Iran [39].

1.2. Water and waves

About 70% of the globe consists of water and there is a constant movement of the ocean. The seastate, characterizing the waves at a specific location, consists of a significant wave height H_s, describing the average wave height, and an energy period T_e, describing the mean length of the waves [40]. The power, P, stored in the ocean waves is calculated as

$$P = \frac{\rho g^2}{64\pi} T_e H_s^2 \,[\mathrm{W}] \quad (1)$$

where ρ is the density of the water [kg/m^3] and g is the acceleration due to gravity [m/s^2] [41]. The mean power of the ocean waves per meter wave front across the globe varies from less than 10 kW/m to over 120 kW/m [42]. Recently, investigations on the wave climate at different locations worldwide have been published [43–45]. It is not only a rough seastate that is interesting when choosing location for a wave power plant. Due to construction, maintenance, cost and distribution - neither the water depth nor the distance to the users can be too large.

The global freshwater scarcity has been estimated, indicating a severe water scarcity in Africa, India, Southeast Asia and western South America [46]. Due to the global wave energy resource and a significant freshwater shortage, the opportunity to combine wave power and desalination is evident. For example, the possibilities of using wave powered desalination in Egypt has been discussed in [47] and on Sicily in [48–50]. There are several countries, experiencing freshwater scarcity, with a coastline suitable for wave power. This implies that it is not really a question of where, rather how and when, to combine wave power with desalination.

The amount of energy needed to power a desalination process depends on the salinity of the feed water [32] and the generated freshwater, as well as the rating of the desalination plant [24]. The total dissolved solids (TDS) in seawater are typically within the range of 35,000 to 45,000 ppm. The water is called brackish if TDS is between 1000 and 35,000 ppm. Freshwater has TDS below 1000 ppm and the water is considered drinkable if TDS is below 500 ppm [7,51].

2. Wave power technologies

In recent years, several wave energy converters (WECs) have been designed and deployed, converting the motion of sea waves to electricity [52]. The WEC affects the environment and careful considerations on its impact have to be taken. In the study of Greaves et al., a summary of the experience on environmental impact assessment in

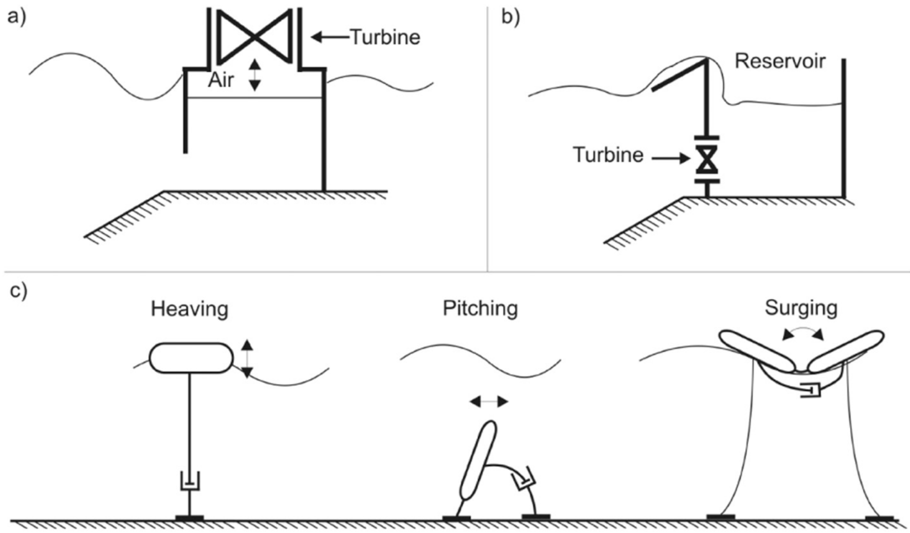

Fig. 1. A wave energy converter can be classified as a) an oscillating water column, OWC, b) an overtopping system, OTS, or c) an oscillating body (wave-activated body) [62].

Europe for wave power was given [53].

There are different ways of classifying WECs [54–56]. For example, as will be used here, a WEC can be classified as one of the three types: oscillating water column (OWC), overtopping system (OTS) or oscillating body (wave-activated body) [57,58]. Babarit discusses the energy absorption of different wave energy concepts [59]. The three types of wave energy converters are depicted in Fig. 1; a) shows the OWC including a turbine for power generation, b) shows the OTS with a turbine and c) shows three different oscillating bodies which can be used to drive a hydraulic system or a linear generator. That is, the power take-off (PTO) can be electrical or hydraulic, and recent studies aim to test different PTOs for WECs [60]. The wave energy converters have to be controlled in order to produce the highest amount of power [58,61]. WEC control can also save the system from some damage. The oscillating water column, the overtopping system and the oscillating body will be described in the following.

2.1. Oscillating water column, OWC

An oscillating water column, or an OWC, is a construction with an open inlet for water under the sea surface, as shown in Fig. 1a). This creates a water column within the structure which oscillates with the motion of the incoming waves. Above the oscillating water column, air is alternately pressurized and forced to flow through a turbine (often a Wells turbine and sometimes an impulse turbine), driving a generator [63]. A review on different oscillating water columns can be found in the work of Falcão and Henriques [64]. Examples of wave power projects including an OWC are LIMPET [65] and Pico [66]. OWCs are currently being studied [67], for example, considering both the hydrodynamic and aerodynamic flows included in the OWC [68], investigating the performance of the turbine [69] and determining the forces acting on the OWC structure, through both experiments and simulations [70].

2.2. Overtopping system, OTS

Wave overtopping, where waves reach some slope and eventually, due to high waves, overtops a structure, can cause damage to coastal cities or ships; the main goal of most research on wave overtopping today is to protect areas from this phenomenon [71,72]. However, wave overtopping has been utilized in the design of wave energy converters [73]. An overtopping system, OTS, or an overtopping device, depicted in Fig. 1b), consists of a reservoir filled with more water as incoming wave crests travels up the slope of the OTS and overtops the structure. The water flows out again through a turbine, generating electricity. Examples of overtopping systems for wave power are Tapchan [74] and Wave Dragon [75].

2.3. Oscillating body

An oscillating body, or a wave-activated body, is a wave energy converter including one part which is directly moving with the ocean waves, such as a buoy or a flap-type device, as can be seen in Fig. 1c). Examples of projects including an oscillating body are the WEC developed at Uppsala University [76] and Oyster [77]. There are different control strategies for the oscillating body WECs, such as latching [78,79], where the WEC is locked mechanically a short time period before it is released, aiming for a body in wave resonance, or declutching [80], where the power take-off is sometimes switched off with the same goal of body-wave resonance. Recent research on oscillating bodies has been performed, for example on how they will affect each other if combined in a park with several oscillating bodies [81–83].

3. Desalination technologies

There are different desalination technologies investigated and designed to generate freshwater from sea- or brackish water, as described for example in the book by El-Dessouky and Ettouney [5]. Inevitably, desalination leads to environmental impact, which stresses the importance in project planning with a sustainability focus when creating a desalination plant [84,85]. There are different techniques for managing the concentrate (or brine) [86], the residue of desalination, which are of great importance as the concentrate can cause environmental issues if it is not taken care of. Some researchers are investigating the possibility and feasibility of using the brine for other purposes [87,88]. There are several desalination processes used today; the three most interesting to combine with wave power are reverse osmosis RO, depicted in Fig. 2a), electrodialysis ED, in Fig. 2b), and mechanical vapor compression MVC, in Fig. 2c), as these processes are driven by mechanical energy (RO and MVC) or electrical energy (ED), which can be harnessed from the motion of the ocean waves.

3.1. Reverse osmosis, RO

Reverse osmosis or RO, sketched in Fig. 2a), is a process where pressurized seawater flows through a semipermeable membrane, creating freshwater [89]. A review on the RO technology was presented by Shenvi et al. [90]. The chemical potential of the solute, dependent on temperature, salinity and pressure, is to be equal on both sides of the membrane. By adding an external pressure to one side of the

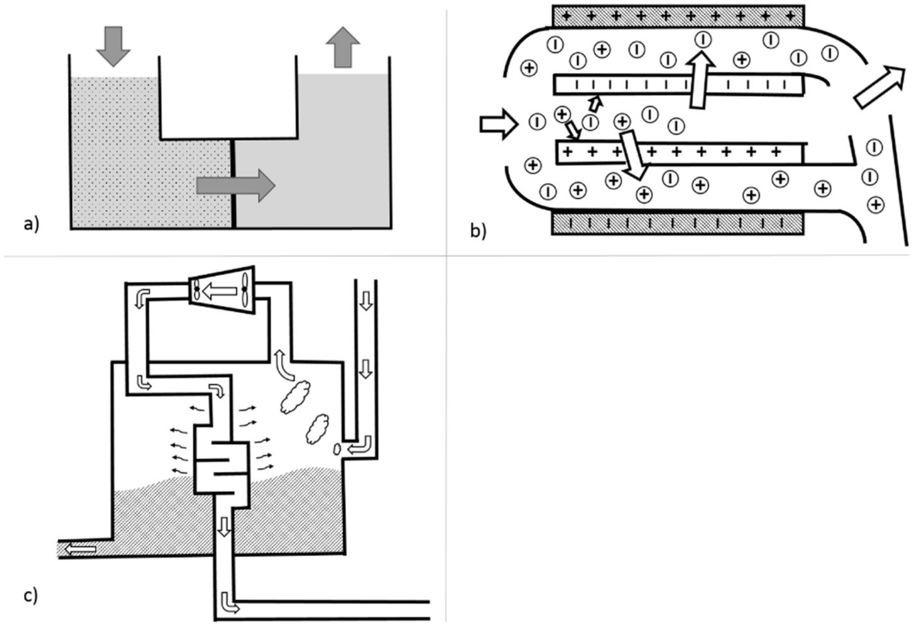

Fig. 2. The desalination processes investigated here are a), reverse osmosis RO, b) electrodialysis ED and c) mechanical vapor compression MVC. Illustrations by Johannes Eriksson.

membrane, clean water will flow to the other side to restore the chemical potential [5]. The product of the RO process is the clean water and the residue is called concentrate or brine, which has a high salinity. Two obstacles with reverse osmosis are membrane fouling and management of the concentrate [91]. With the right pretreatment of the seawater, fouling can be reduced [92]. For several years, the concentrate has been dumped into the sea; with new research showing the negative environmental effects of this, other solutions have been developed to take care of the concentrate [93].

3.2. Electrodialysis, ED

The saltwater includes salt ions; therefore, by applying an electric field, it is possible to separate the salt from the water, which is performed in the desalination process called electrodialysis or ED [5], as shown in Fig. 2b). Ion exchange membranes [94], anion exchange membranes and cation exchange membranes, are placed between anodes and cathodes; when applying an electric field, the positive and negative ions move to the anodes and cathodes respectively, creating brine and freshwater [95]. The salinity of the freshwater can be varied with ED [94].

3.3. Mechanical vapor compression, MVC

Mechanical vapor compression or MVC is a thermal process, where the feed water is evaporated to get rid of the salt; this process is sketched in Fig. 2c). The feed water is first preheated, then sprayed across evaporation tubes, where the water is evaporated [5]. The vapor flows through a demister and to the compressor where it is superheated. The vapor flows through condensation tubes and condenses [96]. The heat from different stages of the process is reused to heat other parts of the process [97]. The MVC process needs energy mainly to power the compressor, but also the heaters, the pumps and so on [98].

4. WEC/DES systems

The combination of wave power and desalination technologies is briefly shown in Fig. 3, inspired by figures describing renewable energy sources and desalination technologies in [7,48].

In the following, a suggestion of a classification of wave powered desalination systems, hereafter referred to as WEC/DES, will be given,

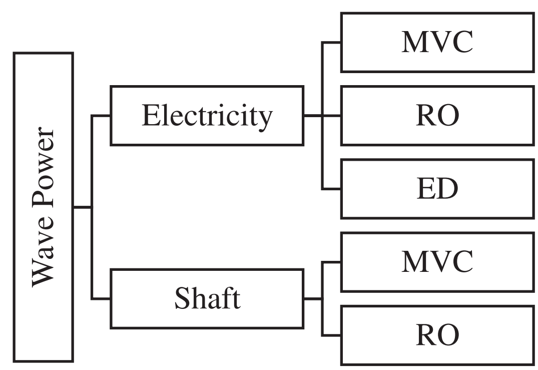

Fig. 3. Combination of wave power and desalination processes.

Table 1
Combining wave power concepts and desalination processes gives three groups of commonly described combined systems – OWCRO, WABRO and WABVC. There are also some potential systems that may be designed in the future.

Wave power technology		Desalination technology		WEC/DES system
Oscillating water column	OWC	Reverse osmosis	RO	OWCRO
Wave activated body	WAB	Reverse osmosis	RO	WABRO
Wave activated body	WAB	Vapor compression	VC	WABVC
Potential future WEC/DES systems				
Oscillating water column	OWC	Vapor compression	VC	OWCVC
Oscillating water column	OWC	Electrodialysis	ED	OWCED
Wave activated body	WAB	Electrodialysis	ED	WABED
Overtopping system	OTS	Reverse osmosis	RO	OTSRO
Overtopping system	OTS	Vapor compression	VC	OTSVC
Overtopping system	OTS	Electrodialysis	ED	OTSED

consisting of the three groups of the combinations that have been proposed and/or created so far, as well as a suggestion on potential future WEC/DES systems which have not yet been designed. An overview of the WEC/DES groups is given in Table 1. The three groups of combined systems suggested in previous literature are here named OWCRO (from Oscillating Water Column – Reverse Osmosis), WABRO (from Wave Activated Body – Reverse Osmosis) and WABVC (from Wave Activated Body – Vapor Compression).

The most commonly suggested type of combined system is WABRO,

Fig. 4. WEC in Vizhinjam, India [101].

where a wave activated body of some shape, such as a buoy or a flapping device, is used together with a pump to pressurize seawater, which is then transported through a reverse osmosis membrane. A WEC/DES system has to be controlled to improve its performance. As an example, the control strategies that can be used for a WABRO, including a floating buoy and a pump, has been investigated [99,100].

Considering the topics discussed in Section 5, each WEC/DES system found in relevant literature was described.

4.1. OWCRO: Oscillating water column – reverse osmosis

An OWCRO plant consists of an OWC wave power plant combined with an RO desalination plant. For this type of WEC/DES plant, the turbine and the plant location (onshore or offshore) has to be considered.

4.1.1. Oscillating water column in Vizhinjam, India

The WEC/DES system in Vizhinjam, Kerala, India, shown in Fig. 4, is an onshore autonomous OWCRO plant built in 1990 to produce freshwater to the harbor community; the WEC/DES plant was described in the paper by Sharmila et al. [101]. The seawater had TDS of 35,000 mg/l and pH of 7.2, and the monsoon seasons were considered when choosing the system. Three different wave power systems were considered in the search of the most suitable design, resulting in the construction of a 3000 tons concrete OWC plant. After different tests of turbines, an impulse turbine was implemented. Moreover, the WEC system consisted of an alternator, a rectifier, a battery and an inverter, generating a single phase 50 Hz, 230 V AC voltage to power the desalination plant. Reverse osmosis was chosen for the desalination process, producing 10,000 l freshwater each day with TDS of less than 500 mg/l and pH of 6.5–7.5. Before the RO process, the seawater was micro filtered and after the process, the water was chlorinated and neutralized. The produced water was tested, proving a good quality. The research was sponsored by the Government of India and performed by the Wave Energy Group at the Indian Institute of Technology in Chennai. Before commissioning, Matlab-simulations and laboratory tests were performed. Moreover, before the RO plant was connected to the OWC, the OWC was tested with other loads to investigate its functionality.

4.1.2. WaveCatcher

The OWCRO concept called WaveCatcher consists of a pump driven by the weight of seawater in a tank. The system is suitable for rural poor communities without the use of electricity. WaveCatcher can be installed by the sea, close to a steep shore or a cliff. An oscillating water column-pump (OWC pump) is used to transfer seawater to a higher altitude where it is released to the tank, acting on the WaveCatcher pump which pressurizes the feed water transferred through a reverse osmosis membrane, generating freshwater [102]. The brine was suggested to be deposited back into the sea. The WaveCatcher project was tested in small scale (1:6), resulting in a maximum pressure of 420 kPa. The authors conclude that the pressure of the prototype should be 600 kPa in order to generate 6000 kPa with a full-scale WaveCatcher, which is needed to pressurize the water for the RO process.

4.2. WABRO: wave activated body – reverse osmosis

A WABRO plant consists of a wave activated body, such as a buoy, combined with a reverse osmosis desalination plant. Two specific considerations for a WABRO system are which kind of wave activated body to use and which kind of power take-off that will be interesting for the system (hydraulic or electric).

4.2.1. Delbuoy

The first known combined system of wave energy and desalination was the WABRO system called Delbuoy, described in several papers, see for example [103,104]. Delbuoy started to produce freshwater 1982 in Puerto Rico. The characteristics of the sites and environment suitable for the system were identified; water depth: 15–20 m, significant wave height: 0.6–1.5 m and energy period: 3–8 s. Delbuoy consisted of a wave activated body, more specifically a cylindrical buoy on the sea surface, connected to a pump on the ocean bed. The size of the system made it possible for deployment from a small fishing boat. The desalination process was reverse osmosis, producing 1.1 m^3 freshwater each day. Firstly, the water was prefiltered when entering the pump - then pressurized. The water was rectified through check valves, a hydraulic accumulator stabilized the pressure and finally, the water, with a pressure of 5500 kPa, was cleaned through the reverse osmosis membrane. 20% of the feed water became freshwater and 80% became concentrate, which was released back into the ocean. The WEC/DES design was developed at the University of Delaware and ISTI Delaware, Inc., with funding from the National Sea Grant College Program, and at the Department of Marine Sciences at University of Puerto Rico with funding from USAID. Financial studies were performed, comparing the Delbuoy with a conventional RO system [104]. The WEC/DES system was modeled and tested before deployment.

4.2.2. Oyster

The Oyster is a wave energy converter flapping back and forth with the motion of the waves, adapted to be at 12 m water depth. It has been suggested that an Oyster can be used to drive a desalination plant, and the cost of freshwater from such a WABRO system was investigated in [105]. The authors discuss the possibilities and limitations in placing the connected desalination device on shore or out in the water by the flapping wave energy converter. The Oyster would drive a pump pressurizing the seawater, which is then rectified through check valves. The level of pressure is stabilized with the use of an accumulator and a pressure relief valve. Thereafter, the water is cleaned through the reverse osmosis membranes and pressure energy-intensifiers are used for energy recovery. An economic model was derived and it was estimated that the minimum cost of water was £0.45 per m^3 [105] and computer simulations of the WEC/DES system were performed.

4.2.3. 3-D WEC and the surge WEC

In the conference paper by Ramudu [106], the ideas of Resolute Marine Energy, Inc. and Atlas Water Systems, Inc., to use two different wave energy converters for desalination, are presented. The goal is to use these WABRO devices in remote coastal areas, firstly in South Africa. Their 3-D WEC consists of a partly submerged floater, connected via three tethers to a power take-off on the bottom of the ocean. The Surge WEC is a paddle flapping in the ocean waves [106].

4.2.4. Floating heave-buoy array

In the paper of Serna and Tadeo, it was suggested that several buoys could be included in a combined wave power- and desalination system [107]. The system would consist of an array of floating buoys connected together to a support structure, which was connected via wires to ballasts on the ocean floor. The buoys would be connected to a hydraulic power take-off, producing electricity which would power a reverse osmosis desalination plant. As the power produced may vary over time, the desalination plant was divided in three parts which all required different power levels and produced different amounts of freshwater. Simulations of the wave energy converter at a suggested location are performed [107]. In a later paper of Serna, Tadeo and Torrijos, another control strategy for a desalination plant driven by renewables was suggested [108].

4.2.5. AaltoRO

The WEC/DES concept called AaltoRO consists of a 25–30 m wide and 10 m high oscillating wave surge converter, called the WaveRoller, which pressurizes the seawater [109]. A so called Adaptive Pressure Generator is used to stabilize the pressure, the water flows through pipelines to the shore, pretreatment chemicals are included and a turbocharger is used for energy recovery. The brine is disposed into the sea. The water is cleaned onshore using reverse osmosis. The optimum pressure for the WABRO system AaltoRO was 4500 kPa, which is lower than the conventional 6000–6500 kPa [109]. The system was simulated for waves in Western Australia and economical calculations estimated the water cost to 0.8 €/m^3.

4.2.6. CETO freshwater

Carnegie was the first company to commercialize wave powered desalination with their CETO Freshwater, consisting of a fully submerged buoy driving a pump, generating pressurized water to the shore. The wave power system was connected to reverse osmosis membranes. The WEC/DES was included in the Perth Project, which aimed to generate both power and freshwater to the naval base HMAS Stirling in Australia [110].

4.2.7. Inertial sea wave energy converter at Ponza island

In the work of Corsini et al., the freshwater supply to the Italian island Ponza is outlined [111]. 3200 people lived on the island at the time, but many tourists visit Ponza in the summer. The water demand was covered by shipping water from Port of Naples. In the paper, two alternatives to the water shipping, both including an RO desalination plant demanding 2.41 kWh/m^3, were investigated: powering the desalination plant with the local grid or to create an autonomously powered WEC/DES plant. The results show that it is possible to cover the freshwater demand with a desalination plant on the island. Also, the estimated price for freshwater from a reverse osmosis desalination plant, at most 1.5 €/m^3 [111], was lower than the cost of freshwater shipped to the island. Moreover, when powering the desalination plant with the wave power concept called ISWEC or inertial sea wave energy converter, resulting in a WABRO system, it was concluded that a water storage is essential for this WEC/DES system to work [111].

4.2.8. Combined wind- and wave power desalination system

A combined floating wind- and wave power system, driving a reverse osmosis system, was suggested by Nikitakos and Stefanakou, with the goal to generate potable water in an environment-friendly and autonomous way [112].

4.2.9. SAROS

EcoH2O Innovations have commercialized an autonomous WABRO system called SAROS (Swell Actuated Reverse Osmosis System) with a focus on sustainability [113], including a floater with a pendulum connected to a hydraulic system. As the pendulum moves with the motion of the ocean waves, seawater is pressurized and cleaned through a reverse osmosis membrane, generating freshwater [114].

4.2.10. Odyssée

The Odyssée WABRO system consists of a buoy connected to a hydraulic cylinder pump. The motion of the waves is transferred to the pump, generating a pressure to drive oil through a hydraulic rotating motor, which is then connected to a pump pressurizing water for an RO cleaning system [115,116].

4.2.11. Uppsala WEC/DES

The wave energy converter designed at Uppsala University, visualized in Fig. 5, is a wave activated body, consisting of a point absorbing buoy floating on the sea surface. The floater is connected via a wire to a linear generator on the ocean bed. The motion of the buoy is transferred through a generator, resulting in an induced voltage. Over the past years, this WEC concept has been extensively studied, using simulations and offshore experiments, including considerations on sustainability and environmental aspects [117,118]. The Uppsala WEC is currently studied at the Swedish west coast, by the town Lysekil, with offshore experiments [76]. The Uppsala WEC/DES project contains an investigation of the possibility to use the Uppsala WEC to generate freshwater, creating an autonomous and sustainable WABRO system. Due to the simplicity of the WEC system, it can be scaled differently and adapted for various locations. Initially, a small-scale WEC/DES plant will be investigated. In the future, larger systems can be studied, including several WECs in a park, connected to a desalination plant.

4.2.12. DEIM WEC/DES for Sicily

Sicily has been facing aridity, resulting in the installation of several desalination plants on the island; in [48,49,50], the use of wave powered desalination was investigated for this region. The waves along the Sicilian coast was outlined, determining the potential for wave energy production and specifically for wave powered freshwater production [48,49,50]. The WEC considered for the desalination process was a

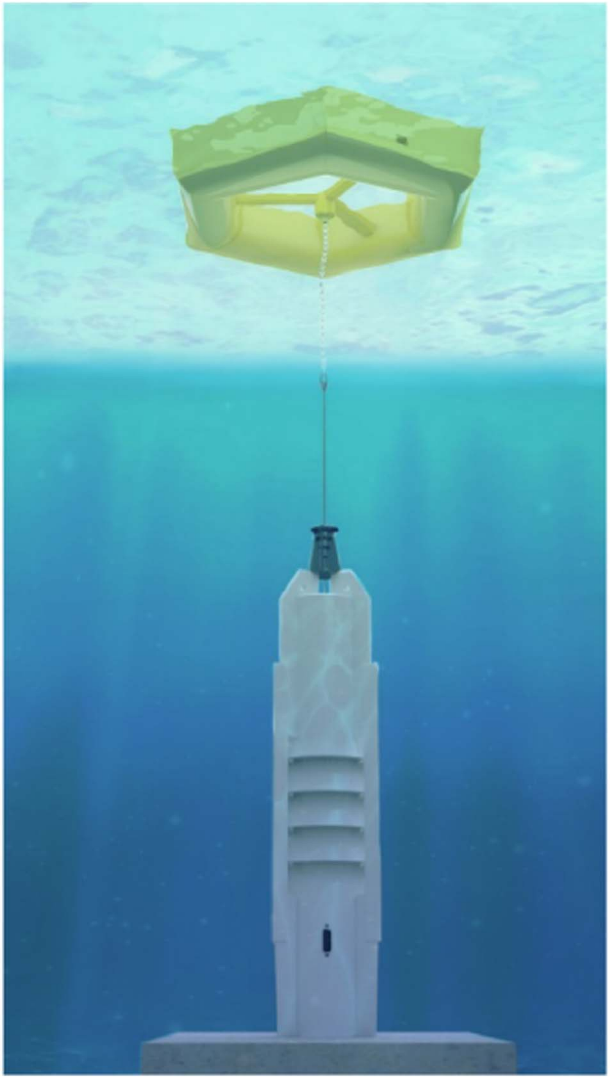

Fig. 5. The wave energy converter designed at Uppsala University, Sweden, including a floating buoy connected to a linear generator.

point absorbing submerged buoy with eight linear generators inside, designed at the DEIM department of the University of Palermo [48,49]. A desalination plant powered by a wave power farm including several DEIM WECs, integrated with a photovoltaic system, was discussed as a case study for Pantelleria Island, including discussions on the environmental aspects of this system compared to one driven by fossil fuels [48,50].

4.3. WABVC: wave activated body – (mechanical or thermal) vapor compression

4.3.1. Edinburgh duck

In 1987, the wave energy concept called the Edinburgh duck, or Salter's duck, was suggested to be used for an ocean wave-driven desalination system, as shown in Fig. 6. The cam-shaped floater was hollow, of large sizes (20 m long and 6 m in diameter) and half-filled with seawater. The nodding motion of the ocean waves was used to compress vapor inside of the floater, desalinating the seawater using vapor compression [119], thus being a WABVC system. In the paper of Cruz and Salter from 2006 [120], new research regarding the directly driven WEC/DES system is described, concluding that a similar desalination principle as the one suggested inside the cam-shaped duck can be obtained inside a cheaper and simpler circular cylinder.

5. Discussion of different WEC/DES topologies

All the described WEC/DES projects are summarized in Table 2, showing the type of project, as well as how far along the projects are and if they are currently ongoing, according to the available literature.

The purpose of these previous projects were, generally speaking, to create a sustainable and autonomous WEC/DES plant to generate freshwater at remote rural areas. Only a few of the previous WEC/DES projects have proceeded all the way from an idea of a WEC/DES plant to generation of freshwater - more specifically Delbuoy, the Vizhinjam project, CETO Freshwater, SAROS and Odyssée have produced freshwater.

In the following, let us consider a WEC/DES project successful if the plant is deployed in full-scale, actually producing freshwater - or at least a project that has proceeded further in the process stated in Table 2 at this moment. The inevitable question is: why are some of these projects more successful than other projects? The more successful projects have discussed more questions in different fields. This can suggest that a holistic and sustainable approach to the WEC/DES research, including a greater number of factors in the research, is more likely to succeed than a work with a more narrow focus. Naturally, a project which has proceeded through several project phases, such as the steps described in Table 2, will have more information to share and discuss in the paper. Including all the steps in Table 2 can be enough in an initial project phase to give a hint on the future performance of the WEC/DES plant and identify necessary improvements before producing freshwater. Therefore, to carefully go through all the questions and considerations of the project, with a sustainability focus, is advisable. All project steps (research, simulations, small-scale tests and final deployment) are pieces towards success.

Some of the discussions in literature regarding the projects lack certain process steps. For example, the research on WaveCatcher, which has not been fully deployed yet, includes small-scale tests but no previous computer simulations. Moreover, the economics or the environmental issues of the project are not discussed thoroughly. This may partially cause the fact that the idea, although technically interesting, did not end up as a full-scale WEC/DES plant. Moreover, environmental concern in all parts of the WEC/DES process is not always included in the projects; for example, AaltoRO and Oyster only mention that the brine will be disposed into the sea – little or no discussions regarding the sustainability of this is described. On the other hand, sustainability is in focus at the webpage of SAROS. Corsini et al. includes an interesting sustainability view on their project as they compare the outcome of different alternatives to cover the freshwater demand on an island. The holistic view on a WEC/DES project has been discussed before. Folley and Whittaker describe the complexity of these projects; they note that some previous WEC/DES projects lack technical information and that Delbuoy and the plant in Kerala might not be sustainable due to economic issues [105].

There are many requirements connected to sustainability, enhancing the complexity of creating a well working plant. A sustainable WEC/DES system is built upon a concern about economic, social and environmental aspects of all project phases, including for example considerations on concentrate management and water quality control. An autonomous WEC/DES plant, as well as any desalination plant autonomously powered by renewables, can suffer from complications of variance in produced power, due to the intermittency of the renewable energy source. However, not including a local electric grid in the freshwater production process have several benefits, especially for rural communities with undeveloped grids. This research provides a framework for future studies on wave powered desalination systems, suggesting a terminology to describe the technical functionality (WEC/DES, OWCRO, WABRO, WABVC and so on). It is concluded that autonomous wave powered desalination can be a feasible and sustainable alternative to more commonly used desalination systems, which often include fossil fuels.

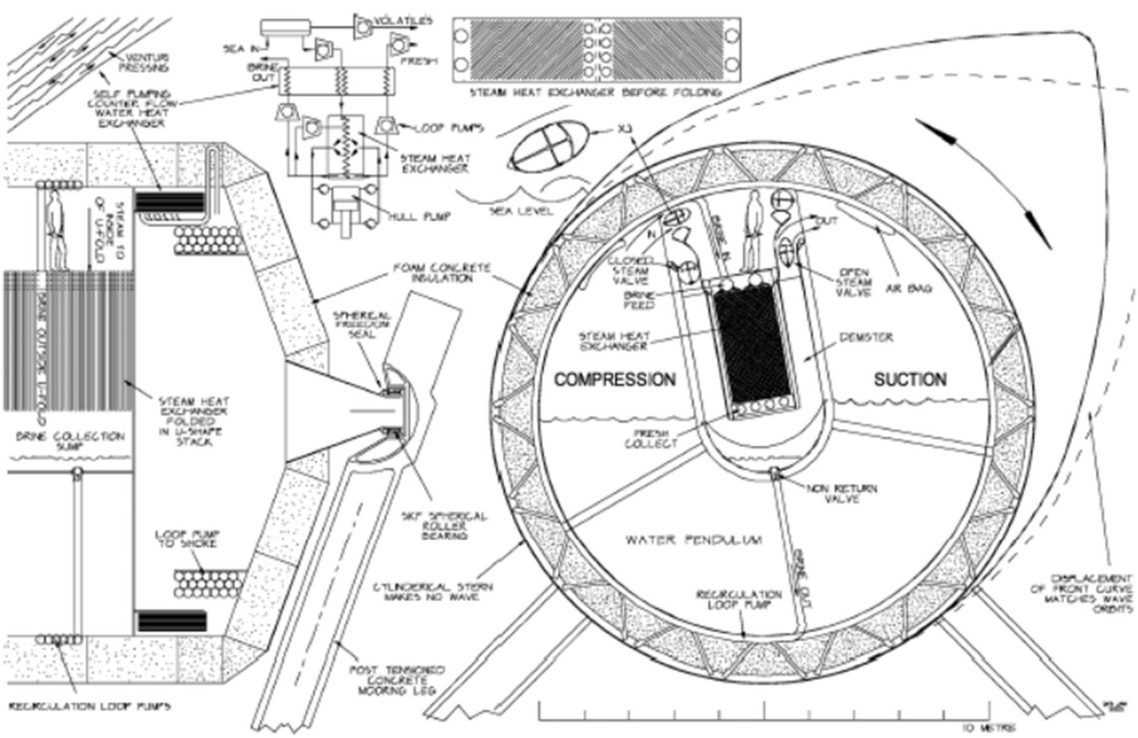

Fig. 6. Sketch of the Edinburgh duck desalination system [120].

Table 2
Reviewing relevant literature, the following table shows how far the WEC/DES projects have proceeded and whether they are seemingly ongoing or not.

Concept	WEC/DES	Research	Simulation	Test	Deployed	Company	Ongoing
3D & surge	WABRO	×	×	–	–	×	–
AaltoRO	WABRO	×	×	–	–	–	–
Buoy array	WABRO	×	×	–	–	–	–
CETO	WABRO	×	×	×	×	×	–
Delbuoy	WABRO	×	×	×	×	×	–
DEIM	WABRO	×	×	–	–	–	–
Duck	WABVC	×	×	–	–	–	–
ISWEC	WABRO	×	×	–	–	–	–
Odyssée	WABRO	×	×	–	×	–	×
Oyster	WABRO	×	×	–	–	–	–
SAROS	WABRO	×	×	×	×	×	×
Uppsala	WABRO	×	–	–	–	–	×
Vizhinjam	OWCRO	×	×	×	×	–	–
WaveCatcher	OWCRO	×	–	×	–	–	–
Wind/wave	WABRO	×	–	–	–	–	–

5.1. WEC/DES considerations

There are many important considerations when combining a wave energy converter and a desalination plant. Some of the topics discussed in reference literature regarding WEC/DES systems can be summarized in these categories:

- Location
- Wave power system
- Desalination system
- Environment
- Cost
- Overall project

However, in large projects, there will always be new questions raised. Although the questions have been divided in different topics, they often span over several fields. Surely, many other questions regarding WEC/DES projects can be added to this description.

Firstly, the **location** of the WEC/DES plant will be investigated (onshore and/or offshore) describing the local area including the seastate and characteristics of the saline water (pH, TDS, hardness, alkalinity and so on), the local freshwater need, possibility of transportation to the site and some information regarding the performance of the existing local electric grid, and whether or not it should be included. Moreover, the **wave power system** used to power the process should be identified, studied and preferably tested; has this WEC been successfully deployed before and what kind of maintenance is needed? The ratings of the wave energy plant (current, voltage, power) has to be investigated, the use of some energy storage units, such as batteries or capacitors, are discussed along with considerations on how the intermittency and fluctuations of the power system can be handled. The **desalination system** used to clean the water has to be outlined. Sustainable desalination systems involve discussions regarding pretreatment, after treatment, energy recovery, fouling and concentrate management. The amount of water produced will be estimated, the transportation, storage and distribution of freshwater should be planned for and the quality of the water has to be carefully tested and secured. In all steps, the **environment** has to be in focus, investigating how each part of the WEC/DES system affects the area. The question is whether the planned WEC/DES system will be sustainable and environment-friendly, or not. The **cost** of the WEC/DES project is important, and it is necessary to know who owns and pays for different parts of the system, and which economic limitations there are. The cost of the produced water can be compared to other alternative ways to get freshwater, and the WEC/DES process has to be economically feasible and competitive. Finally, looking at the **overall project**, several considerations can be discussed, such as the timeline of the project, the competence of the people working with it, the safety on the site and the responsibility of those involved. For example, is there a backup system if the WEC/DES stops working? There may be several regulations that have to be followed. Simulation programs and small-scale prototypes can be used to predict the performance of the WEC/DES plant before final deployment. In short, there are many questions and considerations in need of attention when planning or deploying a WEC/DES plant.

5.2. Directions for future research and development

A significant amount of papers discussing desalination powered by renewables or WEC/DES projects (almost all authors in this field) begin their paper with an outlook of the water shortage situation (and the need of renewable energy) worldwide, with a focus on the great and severe need in many rural areas – this review article is not an exception. The texts show a real concern about humanity and the environment. If the main goal actually is to decrease poverty and the freshwater need, there is a problem with these papers - often ending at nothing more than a suggestion of a solution, a simulation work or similar initial research - rarely in freshwater production. With this strong concern about freshwater production, the main goal of the researchers should be to actually build a prototype of a sustainable and autonomous WEC/DES unit and thereby take necessary steps towards a more equal and sustainable society. Some of the successful projects do not discuss the severe freshwater demand at all; they go straight to describing the technology and the outcome of the research. Maybe a focus on the actual system at a specified location may lead to more successful projects. In either case, researchers with the aim of producing freshwater should do their best to not stop their work at the presentation of a novel WEC/DES idea; they should aim at actually building it in a sustainable way.

The cost of desalinated water from a WEC/DES plant is still not known and there are only a few attempts to commercialize the ideas of freshwater from ocean waves. The technique is rather new and the suggested prices for desalinated water from renewable resources, especially from WECs, varies or are not described fully [105,111,121]. There are many challenges to overcome in order to generate freshwater from an autonomous and sustainable WEC/DES plant. The environmental aspects as well as the issue with power fluctuations from the WEC have to be handled, opening up for more interesting future research in the field of wave power and freshwater.

6. Conclusion

In this study, different WEC/DES systems have been reviewed. Several research projects have been investigated, outlining the possibility of using a certain WEC, as well as other renewable energy sources, to power a desalination process. All investigated literature in the field state that it is possible to create a wave powered desalination system and there is a hopeful future for wave powered desalination. However, there are still many uncertainties on how to actually build these kinds of WEC/DES plants, and there is a necessity of more research.

Acknowledgements

This research has been supported by the Swedish Research Council, VR grant no 2015-03126 and StandUp for Energy.

Conflicts of interest

The authors declare no conflict of interest.

References

[1] M.M. Mekonnen, A.Y. Hoekstra, Four billion people facing severe water scarcity, Sci. Adv. 2 (2016) 1–6, http://dx.doi.org/10.1126/sciadv.1500323.
[2] Q. Chen, Y.Y. Liu, C. Xue, Y.L. Yang, W.M. Zhang, Energy self-sufficient desalination stack as a potential fresh water supply on small islands, Desalination 359 (2015) 52–58, http://dx.doi.org/10.1016/j.desal.2014.12.010.
[3] UN-Water, Water for a sustainable world, The United Nations World Water Development Report 2015, 2015, http://dx.doi.org/10.1016/S1366-7017(02)00004-1.
[4] United Nations General Assembly. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015.
[5] H.T. El-Dessouky, H.M. Ettouney, Fundamentals of Salt Water Desalination, Elsevier, 2002.
[6] W. Lai, Q. Ma, H. Lu, S. Weng, J. Fan, H. Fang, Effects of wind intermittence and fluctuation on reverse osmosis desalination process and solution strategies, Desalination 395 (2016) 17–27, http://dx.doi.org/10.1016/j.desal.2016.05.019.
[7] M.A. Eltawil, Z. Zhengming, L. Yuan, A review of renewable energy technologies integrated with desalination systems, Renew. Sust. Energ. Rev. 13 (2009) 2245–2262, http://dx.doi.org/10.1016/j.rser.2009.06.011.
[8] P.A. Davies, Wave-powered desalination: resource assessment and review of technology, Desalination 186 (2005) 97–109, http://dx.doi.org/10.1016/j.desal.2005.03.093.
[9] M. Folley, J. Cruz, 6.4 Alternative Applications: Desalination. Ocean Wave Energy - Curr. Status Futur. Perspect, Springer, Berlin Heidelberg, 2008, pp. 261–279.
[10] IEA-OES Executive Committee, International Energy Agency Implementing Agreement on Ocean Energy Systems Annual Report 2007, 27 (2007).
[11] H. Balfaqih, M.T. Al-Nory, Z.M. Nopiah, N. Saibani, Environmental and economic performance assessment of desalination supply chain, Desalination (2016), http://dx.doi.org/10.1016/j.desal.2016.08.004.
[12] M.T. Al-Nory, S.C. Graves, Water desalination supply chain modelling and optimization, IEEE 29th Int Conf Data Eng Work 2013, 2013, pp. 173–180, , http://dx.doi.org/10.1109/ICDEW.2013.6547447.
[13] V.G. Gude, Desalination and sustainability - an appraisal and current perspective, Water Res. 89 (2016) 87–106, http://dx.doi.org/10.1016/j.watres.2015.11.012.
[14] M.C. Fragkou, J. McEvoy, Trust matters: why augmenting water supplies via desalination may not overcome perceptual water scarcity, Desalination 397 (2016) 1–8, http://dx.doi.org/10.1016/j.desal.2016.06.007.
[15] M. Faigon, Y. Egozy, D. Hefer, M. Ilevicky, Y. Pinhas, Hadera desalination plant two years of operation, Desalin. Water Treat. 51 (2013) 132–139, http://dx.doi.org/10.1080/19443994.2012.701414.
[16] D. Herold, V. Horstmann, A. Neskakis, J. Plettner-Marliani, G. Piernavieja, R. Calero, Small scale photovoltaic desalination for rural water supply - demonstration plant in Gran Canaria, Renew. Energy 14 (1998) 293–298, http://dx.doi.org/10.1016/S0960-1481(98)00080-9.
[17] E. Mathioulakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: review and state-of-the-art, Desalination 203 (2007) 346–365, http://dx.doi.org/10.1016/j.desal.2006.03.531.
[18] N.C. Wright, A.G. Winter, Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India, Desalination 352 (2014) 82–91, http://dx.doi.org/10.1016/j.desal.2014.07.035.
[19] C. Charcosset, A review of membrane processes and renewable energies for desalination, Desalination 245 (2009) 214–231, http://dx.doi.org/10.1016/j.desal.2008.06.020.
[20] M. Folley, B.P. Suarez, T. Whittaker, An autonomous wave-powered desalination system, Desalination 220 (2008) 412–421, http://dx.doi.org/10.1016/j.desal.2007.01.044.
[21] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability, Desalination 309 (2013) 197–207, http://dx.doi.org/10.1016/j.desal.2012.10.015.
[22] Y.-C. Tsai, C.-P. Chiu, F.-K. Ko, T.-C. Chen, J.-T. Yang, Desalination plants and renewables combined to solve power and water issues, Energy 113 (2016) 1018–1030, http://dx.doi.org/10.1016/j.energy.2016.07.135.
[23] E. Tzen, R. Morris, Renewable energy sources for desalination, Sol. Energy 75 (2003) 375–379, http://dx.doi.org/10.1016/j.solener.2003.07.010.
[24] N. Ghaffour, J. Bundschuh, H. Mahmoudi, M.F.A. Goosen, Renewable energy-driven desalination technologies: a comprehensive review on challenges and potential applications of integrated systems, Desalination 356 (2015) 94–114, http://dx.doi.org/10.1016/j.desal.2014.10.024.
[25] J. Schallenberg-Rodríguez, J.M. Veza, A. Blanco-Marigorta, Energy efficiency and desalination in the Canary Islands, Renew. Sust. Energ. Rev. 40 (2014) 741–748, http://dx.doi.org/10.1016/j.rser.2014.07.213.

[26] I. Khamis, R.S. El-Emam, IAEA coordinated research activity on nuclear desalination: the quest for new technologies and techno-economic assessment, Desalination 394 (2016) 56–63, http://dx.doi.org/10.1016/j.desal.2016.04.015.
[27] K.C. Kavvadias, I. Khamis, Sensitivity analysis and probabilistic assessment of seawater desalination costs fueled by nuclear and fossil fuel, Energ Policy 74 (2014) S24–30, http://dx.doi.org/10.1016/j.enpol.2014.01.033.
[28] R. Nagaraj, Renewable energy based small hybrid power system for desalination applications in remote locations, IEEE 5th India Int Conf Power Electron 2012, 2012, http://dx.doi.org/10.1109/IICPE.2012.6450437.
[29] M.D. Stuber, Optimal design of fossil-solar hybrid thermal desalination for saline agricultural drainage water reuse, Renew. Energy 89 (2016) 552–563, http://dx.doi.org/10.1016/j.renene.2015.12.025.
[30] J.A. Carta, J. González, P. Cabrera, V.J. Subiela, Preliminary experimental analysis of a small-scale prototype SWRO desalination plant, designed for continuous adjustment of its energy consumption to the widely varying power generated by a stand-alone wind turbine, Appl. Energy 137 (2015) 222–239, http://dx.doi.org/10.1016/j.apenergy.2014.09.093.
[31] W. Qi, J. Liu, P.D. Christofides, Supervisory predictive control for long-term scheduling of an integrated wind/solar energy generation and water desalination system, IEEE Trans. Control Syst. Technol. 20 (2012) 504–512, http://dx.doi.org/10.1109/TCST.2011.2119318.
[32] S. Burn, M. Hoang, D. Zarzo, F. Olewniak, E. Campos, B. Bolto, et al., Desalination techniques - a review of the opportunities for desalination in agriculture, Desalination 364 (2015) 2–16, http://dx.doi.org/10.1016/j.desal.2015.01.041.
[33] M.A. Al-Nimr, S.M. Kiwan, S. Talafha, Hybrid solar-wind water distillation system, Desalination 395 (2016) 33–40, http://dx.doi.org/10.1016/j.desal.2016.05.018.
[34] C. Li, Y. Goswami, E. Stefanakos, Solar assisted sea water desalination: a review, Renew. Sust. Energ. Rev. 19 (2013) 136–163, http://dx.doi.org/10.1016/j.rser.2012.04.059.
[35] M. Shatat, M. Worall, S. Riffat, Opportunities for solar water desalination worldwide: review, Sustain Cities Soc. 9 (2013) 67–80, http://dx.doi.org/10.1016/j.scs.2013.03.004.
[36] H. Sharon, K.S. Reddy, A review of solar energy driven desalination technologies, Renew. Sust. Energ. Rev. 41 (2015) 1080–1118, http://dx.doi.org/10.1016/j.rser.2014.09.002.
[37] R. Segurado, J.F.A. Madeira, M. Costa, N. Duić, M.G. Carvalho, Optimization of a wind powered desalination and pumped hydro storage system, Appl. Energy 177 (2016) 487–499, http://dx.doi.org/10.1016/j.apenergy.2016.05.125.
[38] M. Smaoui, L. Krichen, Control, energy management and performance evaluation of desalination unit based renewable energies using a graphical user interface, Energy 114 (2016) 1187–1206, http://dx.doi.org/10.1016/j.energy.2016.08.051.
[39] A. Maleki, M.G. Khajeh, M.A. Rosen, Weather forecasting for optimization of a hybrid solar-wind–powered reverse osmosis water desalination system using a novel optimizer approach, Energy 114 (2016) 1120–1134, http://dx.doi.org/10.1016/j.energy.2016.06.134.
[40] J. Falnes, Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction, Cambridge University Press, 2004, http://dx.doi.org/10.1007/s13398-014-0173-7.2.
[41] J. Falnes, A review of wave-energy extraction, Mar. Struct. 20 (2007) 185–201, http://dx.doi.org/10.1016/j.marstruc.2007.09.001.
[42] A. Cornett, A global wave energy resource assessment, Seal. Technol. (2008) 1–9.
[43] M.A. Hemer, S. Zieger, T. Durrant, J. O'Grady, R.K. Hoeke, K.L. McInnes, et al., A revised assessment of Australia's national wave energy resource, Renew. Energy (2016) 1–23, http://dx.doi.org/10.1016/j.renene.2016.08.039.
[44] A. López-Ruiz, R.J. Bergillos, M. Ortega-Sánchez, The importance of wave climate forecasting on the decision-making process for nearshore wave energy exploitation, Appl. Energy 182 (2016) 191–203, http://dx.doi.org/10.1016/j.apenergy.2016.08.088.
[45] V.M. Aboobacker, Wave energy resource assessment for eastern Bay of Bengal and Malacca Strait, Renew. Energy (2016) 1–13, http://dx.doi.org/10.1016/j.renene.2016.09.016.
[46] UNESCO, Water and jobs, The United Nations World Water Development Report 2016, 2016.
[47] A.S. Bayoumi, A. Incecik, H. Gamal, Shalash K. El, Wave powered water desalination in Egypt, Fourteenth Int Water Technol Conf IWTC 14, Cairo, Egypt, 2010, pp. 191–199.
[48] V. Franzitta, D. Curto, D. Milone, A. Viola, The Desalination Process Driven by Wave Energy: A Challenge for the Future, (2016), pp. 1–16, http://dx.doi.org/10.3390/en9121032.
[49] Viola A, Curto D, Franzitta V, Trapanese M. Sea Water Desalination and Energy Consumption: A Case Study of Wave Energy Converters (WEC) to Desalination Applications in Sicily n.d.
[50] A. Viola, Nexus Water & Energy: A Case Study of Wave Energy Converters (WECs) to Desalination Applications in Sicily, (2016), http://dx.doi.org/10.18280/ijht.34S227.
[51] J. Kucera, Desalination: Water from Water, Wiley - Scrivener Publishing, 2014.
[52] J. Khan, G.S. Bhuyan, Ocean Energy: Global Technology Development Status Final Technical Report IEA-OES Document No.: T0104, (2009) (doi: IEA-OES Document No.: T0104).
[53] D. Greaves, D. Conley, D. Magagna, E. Aires, J. Chambel Leitão, M. Witt, et al., Environmental impact assessment: gathering experiences from wave energy test centres in Europe, Int J Mar Energy 14 (2016) 68–79, http://dx.doi.org/10.1016/j.ijome.2016.02.003.
[54] Lagoun MS, Benalia A, Benbouzid MEH. Ocean wave converters: state of the art and current status 2010 IEEE Int. Energy Conf., 2010, p. 636–41.
[55] N. Khan, A. Kalair, N. Abas, A. Haider, Review of ocean tidal, wave and thermal energy technologies, Renew. Sust. Energ. Rev. 72 (2017) 590–604, http://dx.doi.org/10.1016/j.rser.2017.01.079.
[56] M. Penalba, G. Giorgi, J.V. Ringwood, Mathematical modelling of wave energy converters: a review of nonlinear approaches, Renew. Sust. Energ. Rev. 78 (2017) 1188–1207, http://dx.doi.org/10.1016/j.rser.2016.11.137.
[57] Falcão AF de O., Wave energy utilization: a review of the technologies, Renew. Sust. Energ. Rev. 14 (2010) 899–918, http://dx.doi.org/10.1016/j.rser.2009.11.003.
[58] Y. Hong, R. Waters, C. Boström, M. Eriksson, J. Engström, M. Leijon, Review on electrical control strategies for wave energy converting systems, Renew. Sust. Energ. Rev. 31 (2014) 329–342, http://dx.doi.org/10.1016/j.rser.2013.11.053.
[59] A. Babarit, A database of capture width ratio of wave energy converters, Renew. Energy 80 (2015) 610–628, http://dx.doi.org/10.1016/j.renene.2015.02.049.
[60] H.C. Pedersen, R.H. Hansen, A.H. Hansen, T.O. Andersen, M.M. Bech, Design of full scale wave simulator for testing power take off systems for wave energy converters, Int J Mar Energy 13 (2015) 130–156, http://dx.doi.org/10.1016/j.ijome.2016.01.005.
[61] R. Ekström, B. Ekergård, M. Leijon, Electrical damping of linear generators for wave energy converters - a review, Renew. Sust. Energ. Rev. 42 (2015) 116–128, http://dx.doi.org/10.1016/j.rser.2014.10.010.
[62] C. Boström, Electrical Systems for Wave Energy Conversion, Uppsala University, 2011.
[63] A. Viviano, S. Naty, E. Foti, T. Bruce, W. Allsop, D. Vicinanza, Large-scale experiments on the behaviour of a generalised oscillating water column under random waves, Renew. Energy 99 (2016) 875–887, http://dx.doi.org/10.1016/j.renene.2016.07.067.
[64] A.F.O. Falcão, J.C.C. Henriques, Oscillating-water-column wave energy converters and air turbines: a review, Renew. Energy 85 (2016) 1391–1424, http://dx.doi.org/10.1016/j.renene.2015.07.086.
[65] C.B. Boake, T.J.T. Whittaker, M. Folley, H. Ellen, Overview and Initial Operational Experience of the LIMPET Wave Energy Plant. Proc. 12th Int. Offshore Polar Eng. Conf, (2002), pp. 586–594.
[66] M. Vieira, A. Sarmento, L. Reis, Failure analysis of the guide vanes of the Pico wave power plant wells turbine, Eng. Fail. Anal. 56 (2015) 98–108, http://dx.doi.org/10.1016/j.engfailanal.2015.04.004.
[67] J.C. Henriques, J.C.C. Portillo, L.M.C. Gato, R.P.F. Gomes, D.N. Ferreira, A.F.O. Falcão, Design of oscillating-water-column wave energy converters with an application to self-powered sensor buoys, Energy 112 (2016) 852–867, http://dx.doi.org/10.1016/j.energy.2016.06.054.
[68] F.R. Torres, P.R.F. Teixeira, E. Didier, Study of the turbine power output of an oscillating water column device by using a hydrodynamic – aerodynamic coupled model, Ocean Eng. 125 (2016) 147–154, http://dx.doi.org/10.1016/j.oceaneng.2016.08.014.
[69] Z. Liu, Y. Cui, K.W. Kim, H.D. Shi, Numerical study on a modified impulse turbine for OWC wave energy conversion, Ocean Eng. 111 (2016) 533–542, http://dx.doi.org/10.1016/j.oceaneng.2015.11.005.
[70] D.-Z. Ning, R.-Q. Wang, Y. Gou, M. Zhao, B. Teng, Numerical and experimental investigation of wave dynamics on a land-fixed OWC device, Energy 115 (2016) 326–337, http://dx.doi.org/10.1016/j.energy.2016.09.001.
[71] C. Altomare, T. Suzuki, X. Chen, T. Verwaest, A. Kortenhaus, Wave overtopping of sea dikes with very shallow foreshores, Coast. Eng. 116 (2016) 236–257, http://dx.doi.org/10.1016/j.coastaleng.2016.07.002.
[72] M. van Damme, Distributions for wave overtopping parameters for stress strength analyses on flood embankments, Coast. Eng. 116 (2016) 195–206, http://dx.doi.org/10.1016/j.coastaleng.2016.06.010.
[73] J.P. Kofoed, Wave Overtopping of Marine Structures - Utilization of Wave Energy, Aalborg University, Aalborg, 2002.
[74] J. Falnes, Research and Development in Ocean-Wave Energy in Norway, Int. Symp. Ocean Energy Dev, Japan, 1993.
[75] J.P. Kofoed, P. Frigaard, E. Friis-Madsen, H.C. Sørensen, Prototype testing of the wave energy converter wave dragon, Renew. Energy 31 (2006) 181–189, http://dx.doi.org/10.1016/j.renene.2005.09.005.
[76] E. Lejerskog, C. Boström, L. Hai, R. Waters, M. Leijon, Experimental results on power absorption from a wave energy converter at the Lysekil wave energy research site, Renew. Energy 77 (2015) 9–14, http://dx.doi.org/10.1016/j.renene.2014.11.050.
[77] E. Renzi, K. Doherty, A. Henry, F. Dias, How does Oyster work? The simple interpretation of Oyster mathematics, Eur. J. Mech. B/Fluids 47 (2014) 124–131, http://dx.doi.org/10.1016/j.euromechflu.2014.03.007.
[78] J. Falnes, P.M. Lillebekken, Budal's latching-controlled-buoy type wave-power plant, 5th Eur. Wave Energy Conf. (2003) 233–244.
[79] A. Babarit, A.H. Clément, Optimal latching control of a wave energy device in regular and irregular waves, Appl. Ocean Res. 28 (2006) 77–91, http://dx.doi.org/10.1016/j.apor.2006.05.002.
[80] A. Babarit, M. Guglielmi, A.H. Clément, Declutching control of a wave energy converter, Ocean Eng. 36 (2009) 1015–1024, http://dx.doi.org/10.1016/j.oceaneng.2009.05.006.
[81] W. Chen, F. Gao, X. Meng, J. Fu, Design of the wave energy converter array to achieve constructive effects, Ocean Eng. 124 (2016) 13–20, http://dx.doi.org/10.1016/j.oceaneng.2016.07.044.
[82] M. Göteman, J. Engström, M. Eriksson, J. Isberg, Optimizing wave energy parks with over 1000 interacting point-absorbers using an approximate analytical method, Int J Mar Energy 10 (2015) 113–126, http://dx.doi.org/10.1016/j.ijome.2015.02.001.
[83] F. Kara, Time domain prediction of power absorption from ocean waves with wave energy converter arrays, Renew. Energy 92 (2016) 30–46, http://dx.doi.org/10.

1016/j.renene.2016.01.088.
[84] T. Younos, Environmental issues of desalination, J. Contemp. Water Res. Educ. 132 (2005) 11–18, http://dx.doi.org/10.1111/j.1936-704X.2005.mp132001003.x.
[85] J. Chang, Understanding the role of ecological indicator use in assessing the effects of desalination plants, Desalination 365 (2015) 416–433, http://dx.doi.org/10.1016/j.desal.2015.03.013.
[86] J. Morillo, J. Usero, D. Rosado, H. El Bakouri, A. Riaza, F.J. Bernaola, Comparative study of brine management technologies for desalination plants, Desalination 336 (2014) 32–49, http://dx.doi.org/10.1016/j.desal.2013.12.038.
[87] A.S. Sánchez, I.B.R. Nogueira, R.A. Kalid, Uses of the reject brine from inland desalination for fish farming, Spirulina cultivation, and irrigation of forage shrub and crops, Desalination 364 (2015) 96–107, http://dx.doi.org/10.1016/j.desal.2015.01.034.
[88] A. Shahmansouri, J. Min, L. Jin, C. Bellona, Feasibility of extracting valuable minerals from desalination concentrate: a comprehensive literature review, J. Clean. Prod. 100 (2015) 4–16, http://dx.doi.org/10.1016/j.jclepro.2015.03.031.
[89] L. Malaeb, G.M. Ayoub, Reverse osmosis technology for water treatment: state of the art review, Desalination 267 (2011) 1–8, http://dx.doi.org/10.1016/j.desal.2010.09.001.
[90] S.S. Shenvi, A.M. Isloor, A.F. Ismail, A review on RO membrane technology: developments and challenges, Desalination 368 (2015) 10–26, http://dx.doi.org/10.1016/j.desal.2014.12.042.
[91] S.H. Joo, B. Tansel, Novel technologies for reverse osmosis concentrate treatment: a review, J. Environ. Manag. 150 (2015) 322–335, http://dx.doi.org/10.1016/j.jenvman.2014.10.027.
[92] S. Jamaly, N.N. Darwish, I. Ahmed, S.W. Hasan, A short review on reverse osmosis pretreatment technologies, Desalination 354 (2014) 30–38, http://dx.doi.org/10.1016/j.desal.2014.09.017.
[93] A. Pérez-González, A.M. Urtiaga, R. Ibáñez, I. Ortiz, State of the art and review on the treatment technologies of water reverse osmosis concentrates, Water Res. 46 (2012) 267–283, http://dx.doi.org/10.1016/j.watres.2011.10.046.
[94] A.H. Galama, M. Saakes, H. Bruning, H.H.M. Rijnaarts, J.W. Post, Seawater predesalination with electrodialysis, Desalination 342 (2014) 61–69, http://dx.doi.org/10.1016/j.desal.2013.07.012.
[95] A.H. Galama, G. Daubaras, O.S. Burheim, H.H.M. Rijnaarts, J.W. Post, Seawater electrodialysis with preferential removal of divalent ions, J. Membr. Sci. 452 (2014) 219–228, http://dx.doi.org/10.1016/j.memsci.2013.10.050.
[96] S.H. Mounir, M. Feidt, C. Vasse, Thermoeconomic study of a system for pollutant concentration with mechanical vapour compression, Appl. Therm. Eng. 25 (2005) 473–484, http://dx.doi.org/10.1016/j.applthermaleng.2004.05.011.
[97] H. Ettouney, Design of single-effect mechanical vapor compression, Desalination 190 (2006) 1–15, http://dx.doi.org/10.1016/j.desal.2005.08.003.
[98] D. Zejli, A. Ouammi, R. Sacile, H. Dagdougui, A. Elmidaoui, An optimization model for a mechanical vapor compression desalination plant driven by a wind/PV hybrid system, Appl. Energy 88 (2011) 4042–4054, http://dx.doi.org/10.1016/j.apenergy.2011.04.031.
[99] G. Nolan, J. Ringwood, Control of a heaving buoy wave energy converter for potable water production, Irish Signals and Systems Conference, Dublin, June 28-30 2006, pp. 421–426.
[100] A. Lekka, M.C. Turner, J.V. Ringwood, A class of globally stabilising controllers for the control of wave energy devices for potable water production, Proc IEEE Int Conf Control Appl (2012), http://dx.doi.org/10.1109/CCA.2012.6402400.
[101] N. Sharmila, P. Jalihal, A.K. Swamy, M. Ravindran, Wave powered desalination system, Energy 29 (2004) 1659–1672, http://dx.doi.org/10.1016/j.energy.2004.03.099.
[102] D. Magagna, G. Muller, A wave energy driven RO stand-alone desalination system: initial design and testing, Desalin. Water Treat. 7 (2009) 47–52, http://dx.doi.org/10.5004/dwt.2009.699.
[103] G.R. Mitcheron, C.M. Pleass, D.C. Hicks, Delbuoy: wave-powered seawater desalination system, IEEE (1988) 1049–1054.
[104] D.C. Hicks, G.R. Mitcheson, C.M. Pleass, J.F. Salevan, Delbouy: ocean wave-powered seawater reverse osmosis desalination systems, Desalination 73 (1989) 81–94, http://dx.doi.org/10.1016/0011-9164(89)87006-7.
[105] M. Folley, T. Whittaker, The cost of water from an autonomous wave-powered desalination plant, Renew. Energy 34 (2009) 75–81, http://dx.doi.org/10.1016/j.renene.2008.03.009.
[106] E. Ramudu, Ocean wave energy-driven desalination systems for off-grid coastal communities in developing countries, Proc - 2011 IEEE Glob Humanit Technol Conf GHTC 2011, 2011, pp. 287–289, , http://dx.doi.org/10.1109/GHTC.2011.38.
[107] Á. Serna, F. Tadeo, Offshore desalination using wave energy, Adv. Mech. Eng. 2013 (2013), http://dx.doi.org/10.1155/2013/539857.
[108] A. Serna, F. Tadeo, D. Torrijos, Heuristic control of multi-stage desalination plants under variable available power, STA 2014 - 15th Int. Conf. Sci. Tech. Autom. Control Comput. Eng., Hammamet, Tunisia, 2014, http://dx.doi.org/10.1109/STA.2014.7086793.
[109] M. Ylänen, M.J. Lampinen, Determining optimal operating pressure for AaltoRO - a novel wave powered desalination system, Renew. Energy 69 (2014) 386–392, http://dx.doi.org/10.1016/j.renene.2014.03.061.
[110] Carnegie Wave Energy Limited, Perth Project|Carnegie Wave Energy, http://carnegiewave.com/projects/perth-project-2/, (2015) , Accessed date: 31 October 2016.
[111] A. Corsini, E. Tortora, E. Cima, Preliminary assessment of wave energy use in an off-grid Minor Island desalination plant, Energy Procedia 82 (2015) 789–796, http://dx.doi.org/10.1016/j.egypro.2015.11.813.
[112] N. Nikitakos, A.-A. Stefanakou, Design and economics of a hybrid desalination system applied to an offshore platform, Rev. Bus. Econ. Stud. 2 (2014).
[113] S.A.R.O.S. Desalination, SAROS – Turning Waves into Fresh Water, https://sarosdesalination.com/, (2016) , Accessed date: 13 October 2016.
[114] Water Desalination Report, The International Weekly for Desalination and Advanced Water Treatment Since 1965, 50 (2014), p. 3.
[115] Projet Odysée, Le Projet Odyssée, http://projetodyssee.com/, (2014) , Accessed date: 31 October 2016.
[116] N. Lavars, The Odyssée desalinator: using the power of the ocean to cleanse its own salty waters, New Atlas, 2014 http://newatlas.com/odysse-desalinator-power-ocean-clean/35276/ , Accessed date: 31 October 2016.
[117] M. Eriksson, J. Isberg, M. Leijon, Hydrodynamic modelling of a direct drive wave energy converter, Int. J. Eng. Sci. 43 (2005) 1377–1387, http://dx.doi.org/10.1016/j.ijengsci.2005.05.014.
[118] O. Langhamer, K. Haikonen, J. Sundberg, Wave power-sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters, Renew. Sust. Energ. Rev. 14 (2010) 1329–1335, http://dx.doi.org/10.1016/j.rser.2009.11.016.
[119] A.J. Crerar, R.E. Low, C.L. Pritchard, Wave powered desalination, Desalination 67 (1987) 127–137, http://dx.doi.org/10.1017/CBO9781107415324.004.
[120] J. Cruz, S. Salter, Update on the design of an offshore wave powered desalination device, OWEMES 2006, Civitavecchia (Rome), April 20-22 2006, pp. 6–12.
[121] N.H. Samrat, N. Ahmad, I.A. Choudhury, Prospect of stand-alone wave-powered water desalination system, Desalin. Water Treat. (2015), http://dx.doi.org/10.1080/19443994.2015.1021101.