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# 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*

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ABSTRACT

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).

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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

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

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