Wave-powered desalination: resource assessment and review of technology

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Abstract

The growing scarcity of freshwater is driving the implementation of desalination on an increasingly large scale. However, the energy required to run desalination plants remains a drawback. The idea of using renewable energy sources is fundamentally attractive and many studies have been done in this area, mostly relating to solar or wind energy. In contrast, this study focuses on the potential to link ocean-wave energy to desalination. The extent of the resource is assessed, with an emphasis on the scenario of wave energy being massively exploited to supply irrigation in arid regions. Technologies of wave-powered desalination are reviewed and it is concluded that relatively little work has been done in this area. Along arid, sunny coastlines, an efficient wave-powered desalination plant could provide water to irrigate a strip of land 0.8 km wide if the waves are 1 m high, increasing to 5 km with waves 2 m high. Wave energy availabilities are compared to water shortages for a number of arid nations for which statistics are available. It is concluded that the maximum potential to correct these shortages varies from 16% for Morocco to 100% for Somalia and many islands. However, wave energy is mainly out-of-phase with evapotranspiration demand leading to capacity ratios of 3–9, representing the ratios of land areas that could be irrigated with and without seasonal storage. In the absence of storage, a device intended for widespread application should be optimised for summer wave heights of about 1 m. If storage is available, it should be optimised for winter wave heights of 2–2.5 m.

Keywords: Ocean-wave energy; Renewable energy; Irrigation

1. Introduction

The last decade has seen very significant advances in desalination technology. The cost of desalinated water has halved from about €1/m³ to €0.5/m³ and specific energy usage has also halved from about 8 to 4 kWh/m³. Desalination currently provides about 10 km³/y of freshwater [1] a figure that is growing rapidly with several new projects underway or planned. For example, Spain has recently cancelled its plans to divert the Ebro river, in favour of installing 0.6 km³/y of desalination capacity along its eastern coastline [2]. Around
the Jordan basin, there are plans for some very large schemes including those taking advantage of hydropower connecting the Dead Sea to the Red Sea or to the Mediterranean. In the case of these Dead Sea hydro projects, capacities as large as 1 km$^3$/y have been discussed, enough to satisfy one third of the total demand of Israel, Palestine and Jordan [3].

Impressive though these figures are, they still only represent a very small fraction of worldwide water requirements. It is difficult to calculate accurately the total amount of freshwater used by humans, but an estimate of essential water requirements (as presented by the UN) is based on the observation that each person requires a minimum amount of water, most of which is consumed indirectly in producing food. Availabilities below about 1700 m$^3$/capita/y are generally considered to indicate water scarcity [4]. Multiplied by a global population of 6 billion, this translates to an overall requirement exceeding 10,000 km$^3$, suggesting that desalination currently only supplies of the order of 0.1% of overall freshwater usage. We should not forget that in certain regions the fraction is much higher, making desalination indispensable for the populations concerned. Even in these cases, however, it is mainly restricted to the supply of municipal water. Desalination is rarely used to supply agricultural water, which accounts for some 70% of overall freshwater withdrawals worldwide.

The rapid expansion of population in arid regions means that desalination projects are likely to be proposed on an increasingly grand scale. It is interesting to ask whether this technology will one day represent a large segment of the world water economy, supplying water for all types of end use including irrigation, or whether it will remain a localised solution for the supply of water for mainly non-agricultural purposes.

A fundamental factor affecting the uptake of desalination technology is its energy consumption. For example, suppose that current desalination capacity were to increase 10-fold, reaching about 100 km$^3$/y. This would still only represent a small fraction of worldwide water use. Nonetheless, even with the most energy-efficiency desalination technology available today (reverse osmosis), an electrical or mechanical power input of around 30 GW would be needed, resulting in a consumption approaching 100 Mtoe/y (megatonnes of oil equivalent) of primary energy reserve. This is a very large amount, given that the world’s total primary energy supply is of the order of 10,000 Mtoe/y [5]. Indeed, increased energy prices could result in the reverse scenario, in which existing desalination plants become non-viable and are decommissioned. Table 1 summarises these broad scenarios relating to the future of desalination technology.

Given the simultaneous scarcity of water and of conventional energy resources, there is considerable interest in using renewable energy to power desalination. Although numerous technical concepts have been proposed in this area, most of the experiments to date have been either with solar distillation, or with reverse osmosis powered by electricity from wind or solar sources, as reviewed elsewhere [6,7]. In contrast, this study concentrates on a relatively immature form of renewable energy technology to drive desalination, based on the exploitation of wind-generated ocean waves. Research in the area of wave energy conversion has generally been sporadic. Recently, however, there have been some significant developments in devices for electricity generation [8,9] and these could well spin off benefits to wave-powered desalination.

Waves will generally be available where seawater is desalinated. But the harnessing of wave energy is, as with other forms of renewable energy, expensive in terms of capital plant and the effort needed to develop the technology. It may well require the intervention of governments or international bodies. To enable appropriate policy decisions to be made, it is therefore important to have general information about the nature and potential of the resource in relation to the demand for water.
Table 1
Long-term scenarios regarding global uptake of desalination technology

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Causes</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Multiplication of global desalination capacity</td>
<td>Advances in desalination efficiency overtake increased energy scarcity and cost; or energy is supplied from more sustainable sources such as renewable or nuclear.</td>
<td>Water supply keeps pace with increased demand in arid regions. Alternatively, growth in supply exceeds growth in demand, leading to the amelioration of water-related poverty and reduced reliance on food imports.</td>
</tr>
<tr>
<td>2. Capacity stays roughly constant</td>
<td>Efficiency gains compensate for increases in energy scarcity and cost.</td>
<td>Water stress continues to worsen as populations grow.</td>
</tr>
<tr>
<td>3. Capacity decreases</td>
<td>Substantial increases in energy scarcity and cost cannot be compensated for by improvements to desalination efficiency, making desalination unsustainable.</td>
<td>Decommissioning of plant. Increased food imports from water-rich areas, or implementation of novel agricultural methods using much less water. Water-related poverty likely to worsen.</td>
</tr>
</tbody>
</table>

2. The wave energy resource

Of the 173,000 TW of solar power arriving at the earth’s atmosphere, 114,000 TW is absorbed in the atmosphere, oceans and the earth’s surface. About 1200 TW of this thermal energy is then converted into the kinetic energy of the wind [10]. The shearing action of the wind on the surface of the ocean generates currents and waves, involving energy transfer at a rate of around 3 TW [11]. Thus only a tiny fraction of solar radiation is eventually converted into ocean-wave energy. Nevertheless, ocean waves represent a very intense renewable energy resource.

Ocean waves are mathematically complex; consequently, their complete description requires several parameters. A sea state is conventionally represented by a scatter diagram showing the number of waves occurring at each height and period. Separate scatter diagrams may be presented for each wave direction. A classic source of these diagrams is reference [12]. Such detailed statistics are important for the design of individual wave energy converters. However, for the purpose of a broad resource assessment, wave height is the most important parameter. A source of such data is that based on the GEOSAT missions [13,14], which used radar altimetry to measure the roughness of the ocean surface, enabling wave height to be determined.

An alternative source of data would be from wave buoys that record detailed statistics at their point of deployment [15]. However, such buoys are mostly restricted to the coastlines of industrialised nations and this makes them of little use in the current study. Finally, hindcasting [16], in which waves are calculated from climatic models and measurements of wind, is another possible tool in wave resource assessment. However, hindcasts tend to be carried out as bespoke assignments and this makes them less useful for a general study such as this one. Table 2 summarises and compares these different sources of wave data.

Waves are commonly characterised by the significant wave height, \( H \), which is the mean height of the highest one third of the waves and is also reported to coincide with visual assessments of wave height [17]. This is the only wave parameter that is available over all the oceans and it is
Table 2
Means of measuring ocean waves

<table>
<thead>
<tr>
<th>Method</th>
<th>Coverage and resolution</th>
<th>Type of data provided</th>
<th>Availability</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoys</td>
<td>Mainly around coastlines of developed countries at spacing of 10–100 km typically.</td>
<td>Summaries for hourly intervals. Records go back about 30 years.</td>
<td>Yes Yes Some buoys</td>
<td>[15,18]</td>
</tr>
<tr>
<td>Satellite</td>
<td>Ground track spacing of 163 km at equator decreasing towards poles.</td>
<td>Satellites over flew same point at intervals of 17 days over a 3-year period.</td>
<td>Yes No No</td>
<td>[13,14]</td>
</tr>
<tr>
<td>Visual observations</td>
<td>Concentrated in shipping lanes.</td>
<td>2-monthly for summarized data.</td>
<td>Yes Yes Yes</td>
<td>[12]</td>
</tr>
<tr>
<td>Hindcasts</td>
<td>Hindcasts can be customised to meet requirement of individual projects.</td>
<td></td>
<td>Yes Yes Yes</td>
<td>[16]</td>
</tr>
</tbody>
</table>

Therefore used as the basis for this study. Note that an alternative definition of $H$ is 4 times the root mean square of the water elevation [26].

The power per unit length of wave crest for a wave in a random sea state in deep water is given by:

$$P = \frac{\rho g^2 H^2 T}{64\pi}$$

(1)

where $T$ is the period between waves, $\rho$ is the density of the seawater and $g$ acceleration due to gravity. The following expression relates $T$ to the wavelength $\lambda$:

$$\lambda = \frac{gT^2}{2\pi}$$

(2)

Further, $H$ is related to the wavelength by the wave slope $\beta$ by

$$\beta = \lambda / H$$

(3)

Combining these expressions leads to:

$$P = \frac{\rho H^{2.5} \sqrt{\frac{2g^3}{\pi\beta}}}{64}$$

(4)

The observed value of $\beta$ usually falls within a fairly narrow range of 0.03–0.05. By taking a nominal value of $\beta = 0.04$, we can use Eq. (4) to estimate the power in the waves based on their height alone. With $P$ and $H$ expressed in convenient units of kW/m and m respectively, the relation can be written in the following simple form:

$$P = 2H^{2.5}$$

(5)

For example, locations exist where waves as high as $H = 5$ m frequently occur, yielding a power per unit length of $P = 112$ kW/m. At $H = 1$ m, however, $P$ is reduced to just 2 kW/m. If we specify that the process of conversion of wave energy to freshwater takes place with a specific energy
usage of $Q$, expressed in kWh of wave energy per m$^3$ of water produced, then over a period of 24 h the volume $V$ of water produced will be:

$$V = \frac{48H^{2.5}}{Q}$$

where $V$ is in units of m$^3$/m of coastline/d.

Eqs. (5), (6) are approximations based on the assumption of a constant wave slope of $\beta = 0.04$. The error in this approximation was assessed by applying firstly Eq. (1) and secondly Eq. (5) to several historical scatter diagrams taken from reference [18]. Comparison of the two sets of results showed that the error in $P$ resulting from using Eq. (5) was 2–20%.

The irrigation potential of wave-powered devices deployed along a coastline can be assessed from potential evapotranspiration (PET). The Penman equation expresses evapotranspiration as a sum of two terms, the first dependent on solar radiation and the second dependent on vapour deficit, which is a function of humidity [19]. However, for conditions of high solar radiation, the first term dominates. Since this is usually the case in arid climates, the expression for evapotranspiration simplifies to:

$$E = \frac{D}{D + \gamma} R$$

in which $E$ is the energy associated with the latent heat of water evaporating from a moist surface such as plant leaves, and $R$ is the solar energy arriving at the horizontal surface. The symbol $D$ is the rate of change of saturation vapour pressure with temperature and $\gamma$ is the psychrometric constant $\gamma = 63$ Pa/ºC. The term preceding $R$ in Eq. (7) is only weakly affected by temperature. At a temperature of 20ºC it equals $R = 0.7$ and at 30ºC it equals $R = 0.8$. This indicates that for every 4 units of solar energy incident on irrigated land, approximately 3 units are dissipated in evaporating water. This is the approximation used in the calculation of PET. It enables us to arrive at the following expression for the width $W$ of a strip of coastal land that can be irrigated from the wave-powered desalination device, in terms of the daily irradiation $R$ measured in kWh/m$^2$/d.

$$W = 50 \frac{H^{2.5}}{RQ}$$

where $W$ is measured in km. Consider an example of a climate receiving 6 kWh/m$^2$/d of solar radiation and a wave-powered desalination machine converting waves of height $H = 1$ m into freshwater with an energy usage of $Q = 10$ kWh/m$^3$. This would provide sufficient freshwater to irrigate a coastal strip 0.8 km wide.

The potential of wave-powered desalination must be assessed in relation to the water demands in regions where it is applicable. Water statistics are compiled by the UN at the national level [4]. For specific nations that are both deprived of freshwater and endowed with ocean-wave resources, Table 3 summarises the reported freshwater resource and shortfall, defined as the additional resource need to raise availability to 1700 m$^3$/capita/y. (The figure of 1700 m$^3$ represents the threshold of water scarcity and includes indirect use in food production). Table 3 compares the shortfall against the total freshwater that could be obtained in the limiting scenario of massive exploitation of wave-powered desalination along the complete ocean-facing coastline, as calculated from Eq. (6). The efficiency of conversion is taken as $Q = 10$ kWh/m$^3$ and it is assumed that supply and demand are smoothed over the whole year.

This last assumption can be examined more carefully, since the GEOSTAT data gives month-by-month values of wave height. Month-by-month data of PET has been derived from solar radiation data based on reference [20]. Fig. 1 compares the variation of net PET (accounting for rainfall) and wave energy throughout the year. It is evident that wave energy is generally out-of-phase with water demand for irrigation, to an extent that is quantified in Table 4 by means of
Table 3
Examples of dry countries having significant wave energy resources, indicating the contribution that wave-powered desalination (if fully developed and exploited) could make towards meeting the total freshwater demand in each country. The shortfall is the amount of water needed to increase renewable freshwater to 1700 m³/y/capita, which is the threshold of water scarcity as suggested by the UN. The freshwater potentially available by wave-powered desalination is based on the year-round wave energy available along the length of ocean-facing coastline, assuming that energy can be converted into freshwater at the rate of $Q = 10$ kWh/m³.

<table>
<thead>
<tr>
<th>Country</th>
<th>Renewable freshwater resource* (m³/y/capita)</th>
<th>Population in 2000** (millions)</th>
<th>Shortfall in freshwater (km³/y)</th>
<th>Ocean coastline (approx.) (km)</th>
<th>Freshwater potential from wave-powered desalination (km³/y)</th>
<th>% of shortfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antigua and Bermuda</td>
<td>800</td>
<td>0.07</td>
<td>0.06</td>
<td>40</td>
<td>0.2</td>
<td>333</td>
</tr>
<tr>
<td>Barbados</td>
<td>307</td>
<td>0.27</td>
<td>0.38</td>
<td>40</td>
<td>0.2</td>
<td>53</td>
</tr>
<tr>
<td>Kenya</td>
<td>985</td>
<td>30.7</td>
<td>22</td>
<td>400</td>
<td>9.7</td>
<td>44</td>
</tr>
<tr>
<td>Morocco</td>
<td>971</td>
<td>29.9</td>
<td>21.8</td>
<td>1100</td>
<td>3.5</td>
<td>16</td>
</tr>
<tr>
<td>Oman</td>
<td>388</td>
<td>2.5</td>
<td>3.3</td>
<td>600</td>
<td>2.1</td>
<td>64</td>
</tr>
<tr>
<td>Somalia</td>
<td>1538</td>
<td>8.8</td>
<td>1.4</td>
<td>1600</td>
<td>8.4</td>
<td>600</td>
</tr>
<tr>
<td>South Africa</td>
<td>1154</td>
<td>43.3</td>
<td>23.6</td>
<td>700</td>
<td>7.1</td>
<td>30</td>
</tr>
</tbody>
</table>

* Reference [4]
**Includes only the coastline of the arid western cape

Table 4
Summary of supply-demand matching for wave-powered desalination, assuming demand is driven by evapotranspiration (examples for 4 countries). The irrigation capacity indicates the area of land that can be irrigated from a fully exploited wave-desalination resource based on the length of coastline (see Table 3), and is shown for the cases with and without seasonal storage of product water. The capacity ratio is the ratio between these two cases. The purpose of the storage would be to even out the mismatch in supply and demand throughout the year, as apparent from Graph 1. Without storage, irrigation capacity is constrained by conditions when supply is least favourable in relation to evapotranspiration demand. The amount of storage capacity required is expressed in terms of number of days of desalination plant output.

<table>
<thead>
<tr>
<th>Country</th>
<th>Irrigation capacity (km²)</th>
<th>Capacity ratio</th>
<th>Storage needed (days of output)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with storage</td>
<td>without storage</td>
<td></td>
</tr>
<tr>
<td>Morocco</td>
<td>4700</td>
<td>530</td>
<td>8.9</td>
</tr>
<tr>
<td>Oman</td>
<td>1000</td>
<td>300</td>
<td>3.4</td>
</tr>
<tr>
<td>Somalia</td>
<td>4700</td>
<td>1100</td>
<td>4.3</td>
</tr>
<tr>
<td>South Africa</td>
<td>4400</td>
<td>1400</td>
<td>3.1</td>
</tr>
</tbody>
</table>

capacity ratio, defined as the ratio between the area of land that can be irrigated given plentiful seasonal storage capacity and the area that can be irrigated in the absence of seasonal storage. In the worst case of Morocco, the capacity ratio approaches 9. These findings are to be expected in the sense that waves are generated by winds, which are stronger in the winter when evaporation is lowest. However, exceptions arise in the northern areas of the Indian Ocean, where the swell arriving from the southern oceans means that waves are higher in summer than in winter.
Nevertheless, even there capacity ratios exceed 3. The same calculations yield an estimate of the amount of water storage needed to maximise irrigation potential. This is quantified in terms of the number of days of water output at the average rate of production and is included in Table 4.

3. Technologies of wave-powered desalination

Wave energy stands out from other types of renewable energy resource, not only in terms of the intensity of the primary resource, but also in terms of the conversion efficiencies actually and theoretically obtainable. For comparison, the efficiency of solar energy conversion is commonly held to be limited to 86.7% [21]. This theoretical efficiency is based, however, on assumptions about devices constructed from numerous layers of semiconductor material of progressively varying band gaps. Real devices can only approximate such ideal devices crudely and the record efficiency of photovoltaic conversion actually attained is 35% [22].

Similarly, wind energy converters are normally interpreted as being subject to the Betz momentum theory that places a limit of 59% on achievable efficiency, with real wind turbines achieving efficiencies up to about 50% [23].

In contrast, there appears to be no theoretical reason why wave energy converters cannot reach 100% efficiency in theory [24] and wave tank devices yielding over 80% have been demonstrated in practice [25].

The failure to exploit the wave resource probably stems from the fact that the nations having the most abundant wave resources, such as...
as the UK and Norway, have also been endowed with their own indigenous resources of oil and hydroelectricity. This has given them limited incentive to develop and exploit novel renewable technologies.

Another factor is the lack of niche applications that would have allowed the wave energy market and industry to develop gradually in size. Renewable energy technologies such as wind turbines, wind pumps and solar panels of various kinds have for decades been used in applications such as remote dwellings, radio repeaters and satellites. These gradually evolved into the large-scale applications of today. Further, many wave energy converters tend to require dimensions that scale in proportion to the waves driving them. In this case, there is no progressive scale up from a device studied in a wave tank to one deployed in the ocean. An exception is the Masuda wave device that has been used to power navigation buoys since the 1960’s.

Recently, however, there has been a resurgence of activity in the wave-energy conversion area driven by initiatives such as the Scottish Renewables Obligation [26]. In addition to having very large wave energy resources, the UK is particularly vulnerable to the effects of climate change such as rising sea level. This has spurred significant allocation of funding for pilot projects relating to this and other types of ocean energy resource. There now appears to be the possibility of wave energy converters becoming commercially available in the short to medium term [8,27].

Most of the efforts in wave energy conversion have tended to focus on electricity production [28]. Any such converter could, in principle, be coupled to electrically-driven desalination plant, either with or without connection to the local electricity grid. In this study we focus on stand-alone concepts, with or without intermediate electricity generation. A literature survey revealed six concepts previously or currently under investigation. Five of these have been developed to the point of an experimental model and only one has been fully implemented. As shown in Table 5, the concepts can be categorised according to six types of wave energy converter and two types of desalination technology: reverse osmosis (RO) and vapour compression (VC).

The first reported technology was the DELBUOY, which used oscillating buoys to drive pistons pumps anchored to the seabed [29–32]. These pumps fed seawater to submerged RO modules. Throughout the 1980’s, developments took place including mathematical modelling, wave tanking testing and sea trials in Puerto Rico. But since then the project has not been continued. The oscillating buoy is a relatively inefficient means of wave energy conversion. However, it benefits from simplicity and scalability and works as a broadband absorber that does not need to be tuned to particular ocean conditions.

The second technology reviewed is based on the Salter duck. The duck was originally conceived at the time of the UK Wave Energy Program of the 1970’s and demonstrated that it was possible to achieve an efficiency of wave-energy extraction exceeding 80% using a single degree-of-freedom mechanism [25,33]. The UK government did not pursue this or other wave technologies at that time. However, Salter later proposed a version of the duck for desalination, in which vapour compression equipment is actually housed inside the floating duck [34,35]. Rocking motion will give rise to changes in water level inside the hull of the duck, generating pressures sufficient to drive evaporation and condensation across a falling-film heat exchanger. The process is designed to run at 100°C, but the large size of ocean-going ducks (typically 6–12 m in diameter) will minimize heat losses. Salter points out that the power-velocity characteristic for the vapour compression cycle is very well matched to the physics of duck motion, and proposes novel concepts for heat exchangers and secondary pumping also to be integrated within the duck. Following on from these ideas, Crerar, Low and Pritchard [36–38] investigated further the feasibility of the concept.
Although they lacked resources to make a full-scale duck, they performed mathematical modelling and set up bench models to represent essential features of the duck-driven distillation process. Research on this concept of wave-powered desalination by means of VC is still active and specific energies in the range of $Q = 2.5–10$ kWh/m$^3$ are anticipated. An alternative approach would be to build helical pumps into the ducks, delivering pressurised water to RO units. However, Salter favours vapour compression as a more robust method of desalination [39].

The third technology reviewed is the McCabe Wave Pump, consisting of a three-section hinged barge [40–42]. The two oscillating arms of the floating barge are attached symmetrically to a central section, which is inhibited from pitching by an underslung inertial damping plate. Large forces are therefore developed between the arms and the centre section. These forces are harnessed by means of pistons, pumping either hydraulic oil, for conversion into electrical power, or seawater for feeding RO units. Reference [41] describes wave tank testing of a model 4.3 m long, reporting that the unit can absorb energy exceeding that contained in the impinging wavefront, thus demonstrating diffraction focusing of the waves. The full size device is expected to pump 275,000 m$^3$/y of seawater into RO units at a pressure of 70 bar. Some 35% of this will be desalinated, with the remaining 65% fed through generators to produce electricity in addition to freshwater. For wave heights of 1.5 m, the anticipated outputs are 260 m$^3$/d of freshwater and 30 kW of electricity. The final cost of delivered freshwater is estimated as $1.8/m$^3$ [42]. A prototype device, 40 m long by 4 m wide, has been constructed using standard pontoons. Each pontoon drives double-acting hydraulic pistons, propelling oil in a closed circuit. Monitoring of pressure and flow in the hydraulic circuit has enabled the energy yield of the system to be studied. The device has been operational in the mouth of Shannon, Ireland, for 4 years during which time it has weathered a number of storms. These trials have led to optimisation of the geometry of the full-size device, which will be about 20% longer than the prototype. Since personnel can readily access the floating barge, it will be practical to mount RO units onboard, avoiding the need connect high-pressure seawater hoses to the shore [43]. Actual connection to a RO unit has yet to be attempted.

The fourth technology is the Oscillating Water
Column (OWC) device installed at Vizhinjam, Kerala, under the sponsorship of the Department of Ocean Development (DOD) in 1990 [44,45]. This device is constructed on a concrete caisson connected by a pier to the shore. It works on the principle of a column of air being compressed and decompressed with the rise and fall of the waves. A turbine extracts energy from the air column. The research group at the National Institute of Ocean Technology (NIOT, under the DOD) tested several turbine-generator arrangements and opted in favour of an impulse turbine driving a permanent-magnet brushless alternator rated at 18 kW. The output from the turbine is a constant 130 V and is used to charge a 300 Ah lead-acid battery bank. The DC power is then re-inverted to 230 VAC, 50 Hz, single-phase electricity and used to drive a RO unit. Modelling of the system dynamics was carried out using MATLAB, allowing forecasting of system performance and leading to refinement of the control system. This system contrasts with the other concepts reviewed in that it uses intermediate conversion to electrical energy, therefore allowing construction from relatively standard subsystems and components. When the sea is calm, desalination can be maintained using electricity from a back-up diesel generator. Currently the plant delivers between 4 and 10 m$^3$ of freshwater per day, depending on the period of operation [46]. The Vizhinjam system is envisaged as a solution for small coastal communities and appears to be the only operational wave-powered desalination plant in the world today.

The fifth concept reviewed is the proposal of Sawyer and Maratos [47] to use a tapered channel (similar to the TAPCHAN device as described in reference [26]) or parabolic focussing device to induce flow of seawater within a pipe. They propose to use the water hammer effect to generate large intermittent pressures, by means of a valve that opens and shuts at the end of the pipe. The pressure developed depends on the compressibility of the water and the elasticity of the pipe wall. These authors show that it is theoretically feasible to use the water hammer effect to develop pressures sufficient to drive RO. The technology is very similar to the hydro-ram widely used to lift irrigation water from rivers, although hydro-rams usually generate somewhat lower pressures than those required for RO. Sawyer and Maratos mention the use of several hydro-rams in series to increase output pressure. They also propose combining their concept with underground desalination, to maximise the efficiency of energy recovery. In reference [48] they present an economic feasibility study of this combined concept. They conclude that costs are potentially favourable compared to conventional RO plant and recommend a more detailed technical study.

Finally, a relatively new concept that could be applied to desalination is the Wave-jet, a device resembling the prow of ship [49]. It concentrates waves in manner similar to the Norwegian TAPCHAN [26], but unlike TAPCHAN it can tolerate a certain tidal range. Wave action causes water to be ejected from the prow and the intention is to collect this water in a high-level reservoir. The Wavejet can therefore raise substantial quantities of seawater to a head of a few metres. For the purpose of desalination, it is intended to supply this seawater to a pressure intensifier device, supplying a smaller quantity of seawater at sufficient pressure to run a reverse osmosis unit [50]. A further application of the Wavejet device could be in supplying seawater to solar desalination plant. For example, the Seawater Greenhouse is a concept that integrates solar distillation with water-efficient plant cultivation [51]. It requires a certain electrical input to pump seawater, which could be reduced or eliminated using the Wavejet. The feasibility of combining these concepts is currently being studied.

4. Discussion and conclusions

In the case of the mainland nations assessed, wave-powered desalination has the potential to
supply a significant fraction of national freshwater shortfalls, corresponding to the amount needed to raise freshwater availability to 1700 m³/capita/y. In Morocco, for example, wave-powered desalination could supply 16% of the shortfall, increasing to 64% in the case of Oman. Somalia is the only mainland nation of those studied where potential supply clearly exceeds the shortfall, by a factor of about 6. The island of Antigua and Bermuda has the potential to satisfy its entire water shortage by wave-powered desalination. The same is likely to be true for many other islands, such as the Canaries and the Maldives, where lack of rainfall tends to coincide with abundant wave resource. They were not included in this study explicitly, however, because relevant water statistics were not readily available. Similarly, there are many arid ocean-facing regions belonging to countries that do not figure as being short of water at the level of national statistics. These include regions of the United States, Western Australia, Chile and India to name just a few. Therefore the cases included here provide examples rather than an exhaustive list.

However, the seasonal availability of the wave resource is generally out of phase with water demand for irrigation, as assessed from the potential evapotranspiration figures. The capacity ratios, relating irrigation potential with adequate water storage to that without storage, vary from 3 to 9. Between 100 and 200 days of storage are needed to eliminate the need for overcapacity due to seasonal mismatch.

Whereas wave-powered desalination will tend to produce water uniformly along a coastline, usage will generally be non-uniform and will occur inland as well as on the coast. This too will tend to decrease the useful capacity of the resource, depending on how easily water can be transported from where it is produced to where it is needed. It seems that few general studies have been carried out on the costs of bulk water transportation; however, Zhou and Tol [52] suggest that the energy cost of desalinating water is equivalent to horizontal trans-portion over 100’s of km. This implies that redistribution of desalinated water along a coastline may well be feasible. In contrast, vertical transport of water requires about 1000 times more energy than horizontal transport, which could rule out the use of desalinated water in many inland locations. Note that this restriction applies equally to all kinds of desalination plant, regardless of the energy source driving them. This resource assessment has shown that there could be substantial benefits from developing wave-powered desalination plant. To spread the development costs, it would be beneficial to develop devices for use in a wide range of locations. This will require a specification of typical operating conditions. In the absence of seasonal water storage, wave-powered desalinators should be optimised for the summer when the wave heights are lowest: about 1 m for most of the locations studied. If storage is available, however, it is better to optimise for the larger waves occurring in the winter, since these contain most of the energy. These have heights in the range 2–2.5 m.

The above technology review has shown that little work has been done on wave-powered desalination, compared to the amount done on desalination driven by other sources of renewable energy. Only one system has been identified as currently fully operational. The worsening problems surrounding water and energy resources call for imaginative approaches and solutions. This means that interest in wave-powered desalination is likely to grow. The re-emergence of old concepts is anticipated, together with the proposal of new ones.

5. Symbols

\( D \) — Slope of saturation vapour pressure curve, Pa/°C

\( E \) — Latent heat of evapotranspiration, kWh/m²/d

\( g \) — Acceleration due to gravity, m/s²

\( H \) — Significant wave height, m
\( P \) — Power per unit length of wave crest, k\( \text{W/m} \)

\( Q \) — Specific energy of wave-powered desalination, k\( \text{Wh/m}^3 \)

\( R \) — Solar energy arriving on a horizontal surface, k\( \text{Wh/m}^2/\text{d} \)

\( T \) — Wave period, s

\( V \) — Volume of desalinated water per length of coastline, m\( ^3/\text{m} \)

\( W \) — Width of irrigated coastal strip of land, km

\( \beta \) — Wave slope

\( \gamma \) — Psychrometric constant, Pa/ºC

\( \lambda \) — Wavelength, m

\( \rho \) — Density of seawater, kg/m\( ^3 \)

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References


[16] www.oceanor.no


