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Powering desalination with renewable energy

Purnima Jalihal
Energy & Fresh Water Division, National Institute of Ocean Technology,
Chennai-600 100, Tamil Nadu, India
Corresponding author: purnima@niot.res.in

ABSTRACT

Today, the world is facing two challenges, water stress and climate change, for which anthropogenic causes leading to greenhouse gas emissions, are considered responsible to a large extent. One of the ways to mitigate water stress is desalination. Today, renewable energies are being taken up rapidly to reduce greenhouse gas (GHG) emissions; however, newer forms of energy, like ocean energy, need to be taken up seriously to further augment the clean energy quantum. By coupling desalination with renewable energy, we can simultaneously reduce GHG emissions and alleviate the water stress. The paper discusses the possible hybridization strategies and challenges for the same. Each type of renewable, along with the suitable type of desalination method, needs more study, and complexities for constant powering for water generation need to be addressed.

Key words: Ocean energy, Desalination, Hybrid systems, Greenhouse gas emission, Renewable energy

INTRODUCTION

Today the climate change has become a commonly used terminology referring to long term changes in temperatures and weather patterns. Over a period of time, such changes have been occurring naturally due to the sun's activity or the Earth's tectonics and volcanic activity. But in recent times, anthropogenic reasons are considered the main driver of climate change, prevailing due to the burning of fossil fuels like coal, oil and gas. Burning fossil fuels, generates Greenhouse Gas (GHG) emissions, which contribute to increased temperature levels and climate change. Thus, the need for clean and renewable energies is evident. Today, the solar and wind markets are booming because the technologies have matured and are now getting more and more inexpensive. In this context, more renewable energy forms, including ocean energies, need to play a vital role. Apart from the GHG emissions and affiliated issues, climate change is also playing a detrimental role in water-related issues. On the one hand, there is unprecedented rainfall leading to urban flooding, but in many regions, there is severe water stress. Water stress can be mitigated by augmenting water using desalination and water treatment. Desalination and water treatment systems use fossil fuels for their energy requirements. Thus, in trying to mitigate the effect of climate change, we are worsening GHG since we are increasing the use of fossil fuels. The solution to this is the use of renewable energies for powering desalination and water treatment systems. This paper discusses some hybrid solutions and issues related to realising hybridization, especially using ocean energy for desalination.

RENEWABLE ENERGY FORMS AND DESALINATION SYSTEMS

Renewable Energies

The most commonly known renewable energy forms are solar and wind. Solar PV needs large footprint on land for large powers. It is also available for only a few hours per day. Wind turbines are now installed at several locations in the country due to positive policies by MNRE. Again wind energy is intermittent and storage for standalone systems needs to be addressed. Today offshore floating solar is being studied and also attempts are being made to harness offshore wind energy.

Apart from the solar and wind energy, we need to explore other forms like ocean energy as well. Given the long coastline of India and a huge exclusive economic zone (EEZ), towards the efforts for mitigation of climate change, it is important to develop new technologies for harnessing ocean energy. Energies that can be harnessed from the ocean are wave, tidal, thermal gradient or ocean thermal energy conversion (OTEC), offshore wind and floating solar PV. The latter two forms are not considered ocean energies since the motive force is not sea water. Salinity gradient is also a possible form, but not yet viable. Today developing all of these forms is the need of the hour for coastal regions, and remote locations and islands.

Energy from ocean currents can be extracted using submerged turbines that capture energy from hydrodynamic lift and drag forces acting upon them. The Ocean Energy Systems Technology Collaboration Program under the IEA, on its website (Ocean Energy systems n.d.), gives details of tidal turbines being studied around the world. Towards developing these turbines, a small capacity unit has been indigenously developed in the National Institute of Ocean Technology (NIOT) using computational and experimental techniques. Upon successful testing of the turbine in controlled conditions of the laboratory, it was successfully tested in the MacPherson Strait, South Andaman, India, by suspending the turbine from a floating platform specially designed for this purpose (Dudhgaonkar et al., 2017). Modules of 1–5 kW ocean current turbines are in advanced stages of development since off-grid units of these ratings are of great utility in the Andaman and Nicobar Islands, India (Figure 1).

Figure 1. Hydrokinetic turbine testing at the Andaman Islands, India by NIOT

Wave energy is a prominent form of ocean energy being pursued in several countries in Europe and Asia, and again, the Ocean Energy Systems Technology Collaboration Program (Ocean Energy systems n.d.) gives information on European devices. Wave energies are high in Northern latitudes, but sustaining these systems in severe environmental conditions, is difficult. In India, the wave climate is lower in intensity; hence, design is easier. However, viability has to be addressed for scaled-up systems. For a long time, the Indian wave energy plant was one of the few working plants in the world. It was a fixed oscillating water column device (OWC) installed in the early 1980s and was generating power for a few years. The plant experience led to the development of floating wave energy devices. This was the genesis of the wave-powered navigational buoy developed by NIOT, which is being used extensively by a port off Chennai (Pattanaik et al., 2020).

While solar, wind, and wave energy are irregular, the only base load form of ocean energy is OTEC, viz., Ocean Thermal Energy Conversion. The temperature difference between the sea surface and water at deeper depths remains more or less constant throughout the year in countries like India. This difference can be used to generate power.

The sun warms the surface seawater to an extent that all the energy is captured in a region up to 100 m thickness near the surface. As we go deeper down into the ocean, the water becomes colder. A huge amount of cold water exists at depths of around 1000 m, which is due to the accumulation of ice-cold water melted from Polar Regions. The two bodies of warm water from the surface and cold water from the deep can be used to run the OTEC cycle for generating power. Essentially an OTEC device, converts a low-grade heat source into electricity using a thermodynamic cycle. For tropical countries like India, OTEC can be a good renewable source since this is a baseload source of energy. The temperature difference exists throughout the year, and hence large amounts of power can be harnessed. However, at present OTEC is still in the testing and sea trial stages in the world because of the underlying challenges.

This section has dealt with various form of ocean energy. Worldwide, ocean energy is yet to be commercialised. Small scale devices don’t give much understanding of techno-commercial viability at scale. Perceived risks, huge capital costs, requirement of offshore infrastructure, grid connectivity are all issues to be dealt with for scaling up and commercialisation to happen. Hence, there have been efforts to find alternate markets like aquaculture and desalination. Both these have been studied and are available in the Ocean Energy Systems Technology Collaboration Program (Ocean energy system n.d.).

Desalination

Further, there are largely two types of desalination, viz., the thermal and membrane technologies. Some of the popular thermal technologies (Darwish and Ammar, 2004: Greenlee et al., 2009: El-Ghonemy**,** 2018; Jalihal and Prabhakar, 2019) include, Multi-Stage Flash (MSF), multi-effect desalination (MED) and mechanical/ thermo vapour compression (MVC/TVC). The membrane methods include, reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED) and membrane distillation (MD). These technologies have been deployed around the world and RO has a large market share today. Thermal technologies tend to be more energy-intensive, but are robust and easy to operate. Membrane methods can have environmental impacts and are hard to operate.

Desalination methods to be employed depend on the location, water to be desalinated and quantum of fresh water needed as the main factors. When the location is in the hinterland, brackish water can be desalinated which primarily is being achieved by membrane methods. Needless to say, for coastal locations, seawater desalination is the most suited. In the Indian context, RO membranes are already being manufactured indigenously, however seawater membranes are yet to be commercialized. The energy requirement for brackish water desalination, is far lower than that for the seawater. The issues in seawater desalination are far more complex due to the chemical composition, making it important to understand the quality of intake water. Corrosion is an important issue in seawater desalination systems and need to be addressed by the use of appropriate materials. NIOT has developed a technology using the ocean thermal gradient as described below.

In 2005, a 100 m^3/day land-based plant was commissioned at Kavaratti Island (Figure 2). This plant has been continuously generating freshwater for the past 19 years to meet the drinking water needs of the island community. The water is of excellent quality and has truly changed the lives of the islanders, especially the health of the people. This indigenized technology has been deployed in two more islands of Lakshadweep, namely Agatti and Minicoy, in 2011 and also in Kalpeni and Amini in 2023. The installation of LTTD plants in four other islands (Androth, Chetlat, Kadamat, and Kiltan) is now nearing completion.

In these plants, the thermal gradient between surface and deep layers of the ocean water column that provides huge reservoirs of warm and cold water, was effectively utilized for desalination (Rognoni et al., 2008; Venkatesan et al., 2015; Jalihal, 2022). Figure 3 shows a schematic diagram of the LTTD unit. When seawater at around 28°C is passed through vacuum, it can boil even at this low temperature and the vapour so generated can be condensed using the cold water siphoned from greater depths.

Figure 2. Desalination plant at Kavaratti Island, India

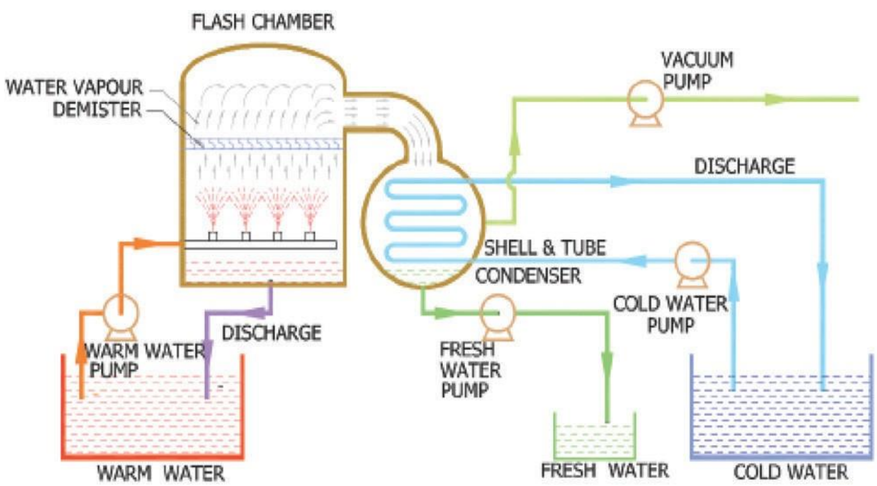

Figure 3. Schematic diagram of the low temperature thermal desalination unit

The water thus generated is of high quality and this cycle can run continuously since the thermal gradient in the ocean is nearly uniform for most of the year. The indigenous LTTD technology developed by NIOT has no requirement for membranes; therefore, has no brine formation and environmental pollution. Thus, the LTTD technology is also environmentally and ecologically safe.

These are the first ever plants in the world, from concept to commissioning, using naturally occurring temperature differences, and they have been completely designed and implemented by NIOT. However, all desalination methods, whether membrane or thermal or any other, need energy which can result in large GHG emissions. For example, CO_2 emissions from desalination using fossil fuels can range from around 2 kg/m³ to 25 kg/m³ depending on the desalination system employed (Shokri and Sanavi Fard, 2023). As can be seen, there are several types of desalination, and their applicability and energy requirements vary. Brackish water desalination is certainly low in energy consumption; however, sea water desalination consumes large amounts of energy. The types of desalination and the energy consumption thereof are location and scale dependent.

Having understood the various renewable energy forms and types of desalination, it is important to understand what can be done to hybridize to eliminate or reduce GHG emissions. Energy requirements of desalination systems, if met by renewable, can alleviate water stress while reducing GHG emissions.

HYBRID SYSTEMS

As stated earlier, treatment and desalination systems are energy-intensive, and hence, the energy-water nexus needs to be addressed. The more we desalinate or treat waste/grey water, the greater the requirement for energy. The time has come, therefore, to address this need by the use of renewable forms of energy. It is now imperative to use renewables to power the desalination and treatment processes. There have been some developments for such hybrid systems, but they are few and need further proliferation in various sectors. The use of renewable energy for desalination is set to expand to help achieve the targets set out in the Paris Climate Agreement and the 2030 Sustainable Development Agenda. Recent examples include, a PV-powered RO system producing 11 m³/day in the Philippines, deployed in 2020, and the Kwinana SWRO plant in Perth, Australia, powered by the 80 MW Emu Downs Wind Farm (Kensara et al., 2021), producing 144,000 m³/day (Ghaithan et al., 2022).

In other locations, like the Canary Islands, where there is a need for desalination as there is a heavy reliance on imported fossil fuel, there is now an increased focus on the deployment of renewable energy, particularly wind and solar, to help meet the demands of the general economy and desalination (Qiblawey et al., 2022). Some specific case studies are presented for various types of hybridized systems, which have been successfully proven and are being used for scaling-up/commercialization.

SOLAR PV–RO

Solar PV systems, connected with RO systems, have been used in several places. This is considered to be one of the best options for renewable energy-powered desalination, particularly for remote areas and the hinterland, as both PV and RO are highly modular and scalable. Using photovoltaic systems can reduce operational costs and improve environmental sustainability. A case study of designing a reverse osmosis (RO) desalination plant, using a Solar Photovoltaic (PV) system, is investigated in Kensara et al. (2021). The RO system is a desalination plant providing pure water to the Shoiaba power generation plant.

The system consists of a PV array connected to an inverter for daytime or batteries for nighttime. The paper discusses various simulations on the system, including PV modules, inverters, batteries, and pumps. The simulations indicate that the PV panels would suffice to power the desalination plant. However, this is only a theoretical study. In Ghaithan et al. (2022), the study assesses the feasibility of powering a large-scale Reverse Osmosis desalination plant using different energy supply systems, including full grid, PV-grid, PV-grid-battery storage, and PV-battery storage. In addition, the study assesses the potential of reforming the power sector in Saudi Arabia by exploring the impact of removing fuel subsidies on the cost of water. The results show that, in the case of fuel subsidies, the final cost of water desalination using PV-grid without a storage system is cheaper than full grid. Thus, there are many examples of attempts at powering RO plants using Solar PV.

Additionally, Clarke et al. (2015) dealt with a standalone energy system, which is completely powered by renewables, and the objective is to meet two external loads: (i) power generation (kWhp), and (ii) desalinated water generation (liter). Their two objectives are to minimize Net Present Cost as well as to reduce CO_2 emissions. The system consists of solar PV arrays with storage.

The power management unit (PMU) powers the RO units for desalinated water as well as the PEM electrolysers. The hydrogen generated, in turn, is used in fuel cells to power the PMU. A detailed methodology has been studied by Tsai et al. (2016), wherein a model is proposed to integrate the operation of a reservoir, hydroelectric power, desalination, and wind power. A balance between seasonal variations is taken into account for powering the desalination system by utilizing the power sources effectively

SOLAR MULTI-EFFECT DISTILLATION

In thermal desalination, solar thermal has been used in a MED system and has been successfully demonstrated. A few years ago, the Department of Science & Technology funded a project to an industry with technical support from NIOT for a Solar Multi-effect Distillation plant at Ramanathapuram in Tamil Nadu (Figure 4). This plant is considered green due to the usage of solar energy and is also safe environmentally since it is a thermal desalination system.

The solar thermal field with a sophisticated tracking system was used to generate steam, which in turn enters the MED system to generate freshwater. Here again, the lack of availability of solar energy throughout the day makes the system depend on another form of energy for augmentation.

The fluctuating and short availability of insolation makes its viability at this point questionable. The footprint for solar systems on land is also high, which is not desirable in this age of high land costs. While thermal systems can generate three times more power than PV per unit area, they need tracking systems for better efficiency.

WAVE POWERED RO

Waves are caused by winds blowing on the surface of the ocean. They are highly irregular in nature with intensities which vary with seasons and geographical location. The global distribution of wave energy indicates that there are many countries that have a coastal wave climate favourable for exploitation of this resource. The wave power devices extract energy directly from the motion of waves at the surface or from pressure fluctuations below the surface.

As far as the Indian scenario goes, for nearly two decades, research has been carried out on an oscillating water column device at a place called Vizhinjam in Kerala as shown in Figure 5. The power generated was also used to run a reverse osmosis-based desalination plant of a capacity 10,000 litres per day. This was the first ever self-sustaining system where power was generated from the sea to make fresh water out of seawater (Sharmila et al., 2004).

Such systems with intermittent power generation need batteries for charging and discharging to keep the system operational for twenty-four hours a day. Standard batteries need to be huge in size for such applications. Thus, storage is an important element for intermittent systems like solar and wave

Figure 4. Solar multi-effect desalination plant at Ramanathapuram, Tamil Nadu, India

Figure 5. Wave energy plant at Vizhinjam, Kerala, India

The need therefore is to think out of the box and explore other forms of clean energy to power desalination systems, and ocean energy is certainly one such arena. However, since wave, solar and wind are all dependent on the time of day, season and other environmental conditions, all these forms of energy need storage or augmentation with the grid power. Base load power such as OTEC does not have such restrictions. Offshore systems like floating solar and wave energy could be amenable to powering sea water desalination systems. However, hinterland brackish water systems can be more easily powered by onshore solar and wind energy systems. Off-grid devices for small powers using hydrokinetic turbines or wave energy devices can serve remote locations like islands very well as green systems to power local small desalination units.

OTEC POWERED DESALINATION

As mentioned earlier, OTEC and LTTD use the ocean thermal gradient to generate power and water, respectively. Since LTTD and OTEC utilize the same resources, it is logical that power generated by an OTEC module can also power an LTTD module from the same plant. Sharing the infrastructure for seawater handling systems, can bring down the overall cost of freshwater generation. Towards this end, NIOT has now undertaken to establish an OTEC-powered desalination plant at Kavaratti. It will be the first ever prototype plant generating power and freshwater utilizing a naturally occurring ocean thermal gradient. The main challenge with OTEC is to generate significant amount of power from a small temperature difference. However, the ocean thermal energy is clean and renewable as the heat source and heat sink possess infinite heat capacities.

The thermal desalination plant being set up in Lakshadweep, will be powered by the ocean thermal gradient. The power generation will use OTEC and desalination will be the LTTD system, eliminating the use of diesel generators. Though the plant has several complexities, it will be completely indigenous and when commissioned, it will produce 0.1 MLD of water using energy from the ocean and will be off grid during operation.

OTEC needs deep sea cold water to maintain around 20 °C as the temperature difference. This deep water is not available at all locations, and hence, for mainland requirements, we need to go offshore. Studies are currently underway to design an offshore platform-mounted OTEC-powered desalination plant to make net power as well as provide energy for the desalination process. While such systems look futuristic, we need to start work and develop appropriate technologies so we can implement viable systems in the near future.

CHALLENGES IN HYBRIDIZATION

While hybrid systems are the way forward, the actual implementation is far from easy. First, let us consider intermittent sources like solar. The solar MED plant works well but only in sunshine hours. The rest of the time, it needs augmentation with other sources of power. If solar PV is used, storage is required for continuous water generation. Similar issues arise with wind energy as well. In India, wind speeds are not very high and energy produced has low plant load factors. This can pose challenges while powering desalination systems since the latter are to be run continuously. Ocean energy resources like wave and tide are also characterised by various degrees of intermittency and these vary from site to site and season to season. This can also impact the choice of desalination technology, which the particular resource is to be hybridized with. A typical scenario with solar PV is the pumping of power to grid and the desalination plant drawing from grid directly. While the model is sufficient to increase the numbers for the renewable share, we are not making desalination emission free.

Another method for utilising wave energy is to directly generate pressure instead of electricity and run the RO membranes to produce fresh water. This method of hybridizing is being attempted in several countries; however, it is still in infancy since quantifying the pressure for different wave climates while scaling up, still poses difficulties. Using wave or tidal energy to directly pressure RO membrane could have technical issues, largely due to the fluctuation in the energy harnessed. If electricity is generated, the fluctuation can be addressed by charging or discharging batteries. When pressure is higher than the desired by the RO unit, dissipation needs to be carried out. Reduced pressure will be detrimental to operation, storage systems are challenging, unlike power equipment and other mechanical challenges also include leak tightness since the systems, including the RO units, may need to be underwater. For OTEC systems, challenges are the high capital costs and optimization of available off the shelf equipment. The biggest challenge is the cold water conduit which is needed to draw cold water from deep ocean depths. The design, installation and robustness of these pipelines are being studied internationally, and this component can be the most complex for an OTEC plant. In the case of offshore plants, power transmission along with water, is also challenging. The OTEC turbines for open and closed cycles are also complex and are yet to be manufactured anywhere. Policy makers are also unable to prioritize funding for technology development due to perceived risks, considering that offshore has severe challenges. Power storage for intermittent sources like wave, wind and solar also becomes important for the constant power requirement of desalination systems.

CONCLUSIONS

In general, there is a need to alleviate water stress today, and desalination is a good solution for the augmentation of water. To reduce GHG emissions, the way forward is using renewable energies; thus, it is important to power desalination systems using renewable energies in this context. The site location, amenable renewable solutions and choice of suitable desalination method, all need to be studied before arriving at a solution. A few researchers discussed the compatibility of different ocean energy technologies with desalination technologies, and they concluded that wave, tidal and OTEC are all amenable to being coupled to RO systems using electricity generated; however, wave and tidal may also utilize the direct pressure generation methodology. They suggest that for thermal desalination systems, OTEC may be the most amenable ocean energy source that can be coupled. In general, for actual implementation, the site selection and TRL for the energy form. will play a role in its utility for hybridization.

It appears that large-scale desalination systems, cannot be hybridized with ocean energy at this point in time. The range of opportunities depends on the cost at which ocean energy can supply power to the desalination system. But there seems to be a generic opportunity for ocean-powered systems for small and micro-scale ranges of desalination plants. If ocean-powered desalination plants can make an entry into the market for small-scale plants, it can present an opportunity for OE-powered systems to become established in a growing market. In fact, this would not only benefit overall cost reduction, but could help in the broader context of the blue economy, like in the aquaculture sector, where water and electricity are both needed at offshore locations.

Further, each type of renewable along with the suitable type of desalination method and site location, needs more study and understanding. The complexities of constant powering for water generation, necessitating storage for intermittent sources, need to be addressed. Technical and commercial viability for base load sources like OTEC, needs optimization along with industry for better components along with offshore installation strategies. Further technology development and research are necessary for a water-stress and GHG-emission-free tomorrow.

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Author Credit Statement

Purnima Jalihal: Data compilation, planning, mapping and manuscript preparation.

Data Availability

Data is based on internal study. It may be made available on reasonable request.

Compliance with Ethical Standards

The author has read the manuscript thoroughly and confirms that it has neither been submitted to any other journal nor been considered for publication. The author adheres to copyright norms.

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