The energy-water nexus: renewable energy and water desalination

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Abstract

The essential connection between energy and water, also defined as the energy-water nexus, has been recognized by scientists and policy makers worldwide. Integrated solutions and policies that consider both energy and water aspects into future planning have been developing at a fast pace. In this paper, we review the state of the art of the energy-water nexus, with particular focus on the integration between renewable energy and desalination technologies. We also model the integration of reverse osmosis (RO) desalination and solar photovoltaics in an edge-of-grid coastal town in Western Australia.

The current literature agrees on the sustainable use of renewable energy sources to improve the water-energy nexus in the context of water desalination. Although the integration of solar and wind energy with desalination technologies is a mature and well-proven solution at both small and large scales, the intermittency and fluctuating nature of wind and solar power still constitute the main technical challenge that has limited the diffusion of renewable energy powered desalination on a large scale. Several successful applications of renewable energy powered desalination in remote, off the grid, locations have tackled the issue of power intermittency by the use of batteries and diesel generators. Such systems often couple reverse osmosis desalination with solar photovoltaic energy. Large desalination plants have been successfully connected to wind farms and grid electricity to secure uninterrupted plant operations, thus meeting water targets in large-scale systems. Our review identifies a knowledge gap in the integration of decentralized energy systems, e.g. rooftop solar photovoltaic, with small scale RO desalination. Such configuration would benefit those regional towns that have historically suffered from weak and unreliable connections to the electricity grid, thus helping them secure both their energy and water requirements.

The modelling exercise on a renewable energy powered RO plant in an edge-of-grid town in Western Australia has identified an operating strategy that maximizes the renewable energy fraction and secures the annual supply of water. The system involves operating the RO unit for six months of the year at a daily variable load and integrating solar energy with grid electricity. Careful evaluation of the RO performance under such operating conditions is necessary to ensure a safe and reliable water treatment process.

A niche in the literature of the energy-water nexus has been identified in the integration of rooftop solar photovoltaic, grid electricity and desalination technologies applied in a regional context. A future study will consider the rollout of rooftop solar photovoltaic installations across the whole town, thus enabling the active engagement of the community by integrating the households' energy demand response patterns to the operations of both rooftop photovoltaics and the desalination unit.

Keywords: energy-water integration; reverse osmosis; solar photovoltaic; grid electricity.

INTRODUCTION

The integration of water and energy within the same decision framework is a priority of current and future resource planning and strategic policy. Often defined as the energy-water nexus [1], the intimate connection between water and energy has been recognized worldwide [1-4]. Rapid population growth, shortage of water availability, as well as considerable changes in global and regional climate, exert increasing pressure on both energy and water sectors, thus leading the scientists and policy makers to think about water and energy systems as connected and coevolving [5-6]. While the need for an integrated approach is global, the high variability in fresh water distribution, energy resources, and population growth calls for regional and local assessments and interventions to identify and implement optimal policy directions and technologies. The integration of water desalination and renewable energy has become a central issue in the energy and water sectors as it improves the energy-water nexus by employing a more sustainable energy source, as well as reducing the operational costs of desalination plants [7]. Despite the growing interest in coupling water and energy aspects within the same decision-making framework, their integration has progressed slowly in practice, often as a consequence of the extreme complexity of the water, energy, and climate as individual as well as integrated sectors [3].

Australia is a highly urbanized country with over 80% of the population living in large cities, located within 50 km of its coasts. Many regional and remote towns in Australia are characterized by weak and unreliable grid connection due to their location at the edge of the grid. Those cities suffer from more power outages compared to big cities. Concomitantly, a decline in rainfall and subsequent drying climate has put unprecedented pressure on the water sector, leading to the widespread construction of small-scale desalination plants as a way to secure water supply. However, such solution to the water problem heavily impacts on the electricity network.

The objective of this study is twofold. First, the state of the art of the integration between renewable energy and desalination technologies has been reviewed and the current research gaps are identified. Then, the feasibility of integrating renewable energy sources in the form of solar photovoltaics and grid electricity with reverse osmosis desalination is investigated in an edge-of-grid town that is subjected to frequent power outages and unreliable grid connection. The integrated system aims to maximize the fraction of renewable energy used to feed the desalination plant. Solar photovoltaics are chosen as a suitable renewable energy source because of their successful applications in small-scale systems as well as because of the declining trend in the price of solar panels [7].

WATER DESALINATION AND RENEWABLE ENERGY

Desalination has become the technology of choice in areas characterized by water scarcity thanks to its maturity, reliability and, in the case of seawater, an abundance of the water source. Desalination technologies are categorized as thermal and membrane desalination: Ghaffour et al. [8] predicted an installed desalination capacity of about 100 million m^3/day in 2015, 68% of which is produced by membrane processes and 30% by thermal processes. Amongst all desalination processes, reverse osmosis (RO) desalination is recognized as the most economical technology [8-10]. Although energy recovery systems allow a two to three fold reduction in the energy consumption, RO desalination still remains an energy-intensive treatment with an energy input of about 2.5-7 and 0.5-3 kWh/m^3 for seawater and brackish water applications, respectively [6].

In order to reduce the dependency of desalination on fossil fuel consumption and its emissions of greenhouse gases, the idea of renewable energy-powered desalination systems (RE desalination) has come forward. Reviews on the integration between renewable energy and water desalination have flourished in the past decade [7, 9-17]. Table 1 summarizes the most recent and thorough reviews considered in this study. A general agreement has been found on the technological maturity of RE desalination systems, however further studies are advisable to augment the operational flexibility of membrane systems when coupled with fluctuating sources of power such as solar and wind. Hybrid plants that combine different renewable sources with traditional electricity sources (e.g., grid or batteries) are often considered the optimal option. The major limitation to the large-scale diffusion of RE desalination has been identified in socio-economic aspects, thus increasing research efforts towards optimization modeling and socio-economic studies is suggested to promote the widespread of RE desalination technology.

The intermittent and fluctuating nature of the RE source constitutes the main technical challenge that has limited the application of RE-RO desalination on a large scale. Membrane manufacturers and RO plant designers advise that the RO plants should operate continuously at full capacity in order to maximize the plant's performances. On the other hand, the inconsistency in the delivery of electricity which characterizes REs causes periods of low water flow through the membrane, thus leading to lower productivity and possibly poorer permeate quality. The predictability of energy fluctuations is therefore a key factor to realize RE-RO systems. The effect of on/off cycling of power is seen immediately in the trans-membrane pressure and water flux, thus no power translates into no water being produced [18]. Conversely, a lag time has been associated with the salt concentration in the permeate [18]: the diffusion of salts through the membrane during shutdowns results in a lower quality of permeate once the plant restarts its operation. To address this issue, Thomson and Infield [19] suggested using an automated valve to reject the produced water exceeding a threshold concentration, thus improving the overall permeate quality of the system. The most critical period for a solar powered RO system has been determined within 1 and 2:30 min of a system restart [20]. After this time, both permeate quality and quantity are set back to their steady-state conditions. Moreover, the higher solar irradiance is available, the quicker the system restarts. Richards et al. [21] showed that a battery-less PV-RO system can tolerate significant fluctuations in solar irradiance (500-1200 W/m^2) and power drops of up to 50% had a minimal influence on permeate water quality.

It is generally expected that membrane life is also affected by power intermittency, however there is only a limited number of studies that address membrane life in RE-RO plants in the long term. Interestingly, unsteady flows are regarded as a method that decreases the concentration polarization on the membrane surface, thus assisting with fouling management and ultimately lengthen membrane life [20].

In order to maximize the plant's performance and minimize the potential damages caused by an intermittent power source, batteries, supercapacitors, and the use of hydrogen as an energy carrier are some energy storage solutions able to provide energy buffer [21-25]. Whenever possible, hybrid-RO plants that combine a variety of REs, with conventional grid as a backup electricity source, have been shown to effectively address the issues of RE availability [26-27]. Interestingly, Gold and Webber [27] found it profitable to use the energy generated by the RE system to meet the demand of the grid, rather than using it directly for water desalination, thus alluding to a decentralized energy system as a potential configuration worth consideration. A knowledge gap is identified as the integration of a decentralized energy systems, e.g. rooftop solar photovoltaic, with small-scale reverse osmosis desalination plants. Such configuration would benefit those regional towns that have historically suffered from weak and unreliable connections to the electricity grid, thus helping them secure both their energy and water requirements.

Table 1. Selected review papers on renewable energy powered desalination.

Authors	Year	Desalination technology	Renewable energy source	Focus of the review
[11] Ghaffour et al.	2015	RO, ED, MSF, MED, AD, MD	Solar; Geothermal	Hybrid systems that incorporate solar and geothermal with innovative desalination technologies
[10] Goosen et al.	2014	RO	Solar; Wind; Wave; Geothermal	Review of technologies with a thorough analysis of social, economic and environmental aspects that are needed to foster the widespread use of RE-desalination
[12] Schafer et al.	2014	RO	Solar; Wind	Review of current RE-desalination solutions with particular attention to developing countries and remote regions
[9] Al-Karaghouli and Kazmerski	2013	RO, ED, MSF, MED	Solar; Wind; Geothermal	Economics of desalination processes on their own as well as integrated with RE
[13] Ma and Lu	2011	RO, ED, MSF, MED	Wind	Review of existing desalination processes coupled with wind energy: principles and technology limitations
[14] Al-Karaghouli et al.	2010	RO, ED	Solar PV	Operational features and system designs of typical PV-RO and PV-ED systems; suitability and optimization for PV operation
[15] Gude et al.	2010	RO, ED, MSF, MED	Solar; Wind; Geothermal	Review of principles and detailed analysis of selection criteria for RE-desalination, with focus on costs for desalination processes with capacities in the range 200 - 40,000 m^3/day
[16] Charcosset	2009	RO, ED, MD	Solar; Wind; Wave; Hydrostatic pressure	State of the art review on membrane processes: principles, plant design and implementation
[17] Eltawil et al.	2009	RO, ED, MSF, MED	Solar; Wind; Biomass; Geothermal	State of the art technologies in desalination and renewable energy, with emphasis on economics and system capacities
[7] Ghermandi and Messalem	2009	RO	Solar	In depth analysis of real scale plants that combine solar energy and RO desalination

RO: reverse osmosis; ED: electrodialysis; MSF: multi-stage flash; MED: multi-effect distillation; AD: Adsorption desalination; MD: membrane distillation; PV: photovoltaic

CASE STUDY

The country town of Denmark is a small coastal town located in the Southern Region of Western Australia, about 400 kilometers south of Perth (Figure 1). The town's electricity is supplied by a coal-based power plant located 300 km north, which characterizes Denmark as an edge of grid community that faces considerable reliability and power quality issues. A community-driven and owned wind farm has been operating since February 2013, supplying about 30% of the 14 gigawatt hours annual electric energy of Denmark. The water demand is currently supplied by two freshwater dams, Quickup Dam and Denmark River Dam, located 7 km north of town (Figure 1). Water resources have been increasingly under stress, and in 2014 the town experienced its second driest year on record. The current proposal of the water service provider to tackle the issue of water shortages is to deploy a brackish RO plant that treats the river water, which is characterized by peak salinity values as high as 1,500 mg/L.

Figure 1. Location of the study site.

In this study, RO desalination of river water has been considered as the primary source of water supply to Denmark and the integration of the proposed RO plant with a photovoltaic solar-based energy has been modeled. A PV-grid system is considered as a potentially suitable solution to provide energy to the RO plant. The PV system is proposed as a centralized PV array.

As the objective of the system is to maximize the contribution of REs to the RO plant, three alternative configurations are modeled:

- *Case 1* considers the RO plant is running 24/7 for the entire year at a constant load.
- *Case 2* investigates the opportunity to run the RO plant 24/7 for six months only, from November to April being the summer dry season, at a capacity that is double the one of *Case 1*. This configuration will guarantee the annual water demand is met while maximizing the use of PVs.
- *Case 3* looks at further improving the use of PVs by defining a daily routine of the RO plant operations. The RO plant works at full capacity when the solar power is maximum (i.e., for 4 hours a day, from 10 am to 2 pm) and at 50% capacity for the rest of the day with electricity sourced from the PV and grid. The RO plant runs 24/7 for six months of the year.

ROSA software from DOW Chemical Company is used to design and model the RO plant [28-29]. The current annual water demand of Denmark is set at 354,552 m^3. The feed flow rate is calculated for each configuration based on the annual water demand and a recovery rate of 75%. A feed flow rate of 54 and 108 m^3/h is calculated for *Case 1* and *Case 2*, respectively. Two feed flow rates are calculated for *Case 3*: a 100% capacity flow rate (185 m^3/h) that is treated for 4 hours/day, and a 50% capacity flow rate (93 m^3/h) that runs for 20 hours/day.

The energy supply system is modelled by HOMER [29,30]. The costs of initial setup, replacement, and other technical details of each energy component are derived in [30]. The operation and maintenance (O&M) costs are considered as 1% of the capital costs. The project lifetime is set to 25 years.

RESULTS AND DISCUSSION

The power consumption of the RO plant varies for each case. The design details (e.g., number of membranes and number of stages) are varied in each simulation in order to meet the design requirements (e.g., constant crossflow and minimum flow in each membrane element). The permeate flux is kept at 20-25 $L/m^2/h$.

The power and energy consumptions are listed in Table 2 and are related to the water desalination process (the electrical consumption of water pumping and transport is excluded from the current study). One of the objectives of this study is to maximize the fraction of RE used to supply the RO plant. To this end, *Case 2* and *Case 3* allow a larger exploitation of the solar resource by running the RO plant only when the output power of the PV system is at its maximum. Although *Case 2* and *Case 3* have a higher power consumption than *Case 1*, these alternative configurations aim at supplying their additional power demand from the PV system.

Table 2. Power requirement of the RO plant under different scenarios.

	Feed flow rate (m^3/h)	Feed pressure (bar)	Power consumption (kW)	Specific energy consumption (kWh/m^3)
Case 1	54	13	25	0.6
Case 2	108	13	50	0.6
Case 3	93 - 185	11 - 15	36 - 98	0.5 - 0.7

Table 3 summarizes the outcomes of the modeling of the energy components. In a grid-only system, the cost of energy (COE) over the project lifetime is the same for each case and equal to

0.29 \$/kWh. This is because the same energy is required annually in all cases. Amongst all simulations, the lowest COE is found for the PV-grid system in *Case 3* (0.22 \$/kWh). Although the highest capital costs are associated with this alternative due to the largest installation of PV system and inverter, the O&M costs are substantially lower, and the total net present cost (NPC) for *Case 3* is 12 and 14% lower than those of *Case 1* and *Case 2*, respectively. Moreover, 75% of the total energy required in *Case 3* is supplied by RE, making this alternative more sustainable over the project lifetime. Interestingly, *Case 2* has slightly higher costs than *Case 1*, which makes a tiny difference between these two choices. Among these two, *Case 1* seems to be preferable than *Case 2*.

Table 3. Optimization results for the power supply system to the river water RO plant.

	System type	PV capacity (kW)	RE fraction (%)	Inverter capacity (kW)	EPgrid (MWh/y)	ESgrid (MWh/y)	Capital costs (k\$)	O&M costs (k\$/year)	NPC (k\$)	COE (\$/kWh)
Case 1	Grid	0	0	0	219	0	0	64	812	0.29
	PV - Grid	115	55	50	136	47	145	39	649	0.23
Case 2	Grid	0	0	0	217	0	0	63	805	0.29
	PV - Grid	135	59	60	139	77	171	39	667	0.24
Case 3	Grid	0	0	0	201	0	0	58	746	0.29
	PV - Grid	190	74	100	98	134	252	25	570	0.22

PV: photovoltaic; RE: renewable energy; EPgrid: energy purchased from grid; ESgrid: energy sold to grid; O&M: operations and maintenance; NPC: net present cost; COE: cost of energy

Based on the modeling results, the optimally integrated water-energy configuration is the one proposed in *Case 3*, which considers a daily variable water flow rate feeding into the RO plant, with the RO operations being limited to the summer months of November to April. This configuration maximizes the RE fraction to nearly 75% and minimizes the total NPC and COE over the lifetime of the project while guaranteeing the production of the required annual water demand to Denmark.

The optimal case from an energy perspective is certainly the most challenging one for the operation of the RO plant because of the daily variation of the water feed flow rate, and the six-month halt of the plant. Based on the available literature and common practice, the feasibility of an RO system under a daily variable load and supplied by a PV-grid system (*Case 3*) is in line with general practice and recent discoveries [18,20,21]. However, a unified agreement of RO performance under power fluctuations has not been found yet, and the issue of variable water feed flow has to be assessed on a case-by-case basis. Pilot trials and sharing practical knowledge are required to shed light on optimal RO operations. Also, it is pivotal for membrane manufacturers and RO plant operators to move towards increased flexibility of membrane systems in order to improve the integration of RO plants with RE and sustainable desalination systems.

A centralized PV system is considered in the analyses carried out in HOMER. Assuming that each 1.8 m^2 PV panel can provide 0.25 kW and considering a inverter efficiency of 90%, the size of the area required by the PV system of *Case 3* becomes approximately 1,600 m^2. Irrespective of the availability of the required land, and following the findings of [27], a novel scheme can be considered for the PV-RO system as modeled in this study. Such scheme considers a decentralized PV system to be composed of many distributed rooftop PVs installed on private dwellings within the community. In this way, each residential customer can use solar energy when it is needed and available, while the remaining excess generation is fed back to the grid with the RO plant being always fed by the grid.

CONCLUSION

The integration between renewable energy and desalination technologies is a vital technological development within the energy-water nexus framework. Renewable energy powered desalination guarantees a sustainable solution to a safe water supply worldwide, whilst improving the sustainability of the energy supply. Recent reviews agree on the technological maturity of RE desalination systems, however further studies are advisable towards improving the operational flexibility of membrane systems when coupled with fluctuating sources of power such as solar and wind. Improved membrane manufacturing technologies combined with hybrid plants that integrate different renewable energy sources are often considered the optimal option.

This study shows that a RO plant characterized by a daily variable load and operating during the warmest six months is capable to meet the annual water demand as well as maximize the renewable energy fraction by solar PV. This configuration maximizes the RE fraction to nearly 75% and the total COE is modeled at 0.22 $/kWh. The feasibility of an RO system under a daily variable load and supplied by a PV-grid system is in line with general practice and recent discoveries.

A future study will consider the rollout of solar PVs across the small town of Denmark. To the best of the authors' knowledge, no modeling and optimization studies that include both technical as well as management issues have been done on a system that integrates water treatment with solar energy in the form of rooftop PVs. The vision of a decentralized rooftop PV system incorporated within the community is expected to enhance the integration of the water system (i.e., the RO plant) and energy system (i.e., rooftop PVs) with the active engagement of the community, thus promoting sustainable planning and operations in the context of the energy-water nexus.

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