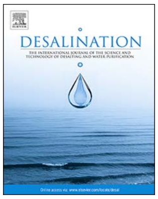
ARTICLE IN PRESS

Desalination xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Desalination

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



Selecting an economically suitable and sustainable solution for a renewable energy-powered water desalination system: A rural Australian case study

Roberta Fornarelli*, Farhad Shahnia, Martin Anda, Parisa A. Bahri, Goen Ho

School of Engineering and Information Technology, Murdoch University, South Street Campus, 90 South Street, Murdoch 6150, Western Australia, Australia

ARTICLE INFO

Keywords:
Energy-water nexus
Edge-of-grid rural networks
Reverse osmosis desalination
Rooftop solar photovoltaic
Wind energy

ABSTRACT

Renewable energy (RE) powered reverse osmosis (RO) desalination is rapidly evolving as an attractive energy-water nexus solution that combines the sustainability of RE and the maturity of RO. The intermittent and fluctuating power of RE, the variable operation of RO systems and the social acceptance of RO, commonly perceived as an energy intensive process, are some of the challenges currently faced by scientists and decision makers. The objective of this study is to identify an energy-water system that is cost-effective, sustainable and socially accepted in a rural community of Australia. The numerical analysis is based on one year (2016) data of energy demand of the community. The size and energy demand of the RO plant is assumed based on the 2016 water demand. A modelling approach that can be readily available and simple to use by the regional energy and water utilities is developed. Out of the seven assessed energy configurations, the most cost-effective system includes a hybrid RE-RO system characterized by grid electricity, a 2.4 MW wind and a 2.8 MW distributed rooftop solar photovoltaic (RTPV) system to supply the 14 GWh and 1.2 GWh annual energy demand of the community and RO plant, respectively. A system of RTPVs distributed across the community is suggested as an option to improve the social acceptance of the RO by directly engaging the consumers in the supply of their own energy and water needs. The RO is simulated to operate as a deferrable electrical load, whose feed flow rate and operating pressure vary (within admissible limits) as a function of the renewable energy excess and the end-user's energy consumption. The proposed energy-water system aims to provide a sustainable and economical solution whilst targeting the cultural gap between community members and decision makers that has been hindering desalination projects in Australia's rural communities.

1. Introduction

Integration of water and energy within the same decision framework has become a priority of current and future resource planning and strategic policy. Often defined as the energy-water nexus to describe a full energy and water value chain, the intimate connection between water and energy has been recognized worldwide [1–5]. Water is needed to produce energy (e.g., extracting fossil fuels, cooling power plants) and energy is needed to secure water supply, treatment and distribution [6]. Rapid population growth, shortage of water availability and significant changes in global and regional climate exert increasing pressure on the energy and water sector, leading both scientists and policy makers to think about water and energy systems as connected and coevolving [7–8].

The vast majority of the existing urban water and energy supply schemes is centralized in nature. Current centralized water systems collect water from fresh, brackish or seawater sources and treat it to potable quality prior to transporting it to distant urban areas. Similarly, energy supply systems are centralized in large power stations and, more recently, in wind or solar-type renewable energy farms (REs). Centralized water and energy schemes have been increasingly challenged by the high variability in fresh water distribution, energy resources, and population growth, thus calling for new regional and local assessments to identify optimal policy directions and technologies [5]. In Australia, where the electrical energy is largely produced by coal combustion, a continuing expansion of centralized systems that use conventional water and energy technologies is considered inefficient, uneconomical and unsustainable [5]. A new interest towards decentralized and diversified water and energy solutions has emerged as cost effective, beneficial and possibly more sustainable and socially accepted than traditional centralized systems [9–11]. In this context, the engagement of the local community and acceptance of the proposed

---

Abbreviations: COE, cost of energy; NPC, net present cost; RE, renewable energy system; PV, solar photovoltaic system; RTPV, rooftop solar photovoltaic system; RO, reverse osmosis desalination; SEC, specific energy consumption; CS, current system

* Corresponding author.

E-mail address: R.Fornarelli@murdoch.edu.au (R. Fornarelli).

https://doi.org/10.1016/j.desal.2017.11.008
Received 28 June 2017; Received in revised form 17 October 2017; Accepted 4 November 2017

Please cite this article as: Fornarelli, R., Desalination (2017), http://dx.doi.org/10.1016/j.desal.2017.11.008

Table 1
Selected reviews on RE-powered desalination.

Ref.	Desalination technology[a]	RE source	Focus of the review
[12]	RO	Solar, wind, wave, geothermal	Comprehensive review of technologies with focus on social, economic and environmental knowledge gaps
[13]	RO, ED, MSF, MED	Solar, wind, geothermal	Economics of stand-alone RE-powered desalination processes
[14]	RO, ED, MSF, MED, AD, MD	Solar, geothermal	Hybrid systems that incorporate solar and geothermal with innovative desalination technologies
[16]	RO	Solar, wind	Review of current RE-desalination solutions with particular attention to developing countries and remote regions
[17]	RO	Solar, wind	Modelling of hybrid systems
[18]	RO, ED, MSF, MED	Wind	Review of existing desalination processes coupled with wind energy: principles and technology limitations
[19]	RO, ED	PV	Operational features and system design of PV-RO and PV-ED systems; optimization of PV operation
[20]	RO, ED, MSF, MED	Solar, wind, geothermal	Review of principles and detailed analysis of selection criteria for RE-desalination, focus on medium-large size desalination plants
[21]	RO, ED, MD	Solar, wind, wave	State of the art review on membrane processes: principles, plant design and implementation
[22]	RO, ED, MSF, MED	Solar, wind, biomass, geothermal	State of the art technologies in desalination and RE, with emphasis on economics and system capacities
[23]	RO	Solar	Assessment of real scale plants that combine solar energy and RO desalination
[24]	RO	Wind, solar, hybrid	Review of potential solution strategies to wind intermittence and fluctuation on RO plants: energy storage, hybrid systems and variable operations
[25]	RO	Solar	Experimental system on solar desalination with focus on maximizing water production rate for remote areas
[26]	Solar still	Solar	Alternative desalination method for sea and brackish waters with focus on a zero liquid discharge process

[a] RO: reverse osmosis; ED: electrodialysis; MSF: multi-stage flash; MED: multi-effect distillation; AD: Adsorption desalination; MD: membrane distillation.

energy-water solutions are becoming key factors for the successful implementation and operation of energy and water supply systems [12].

Reverse osmosis desalination (RO) systems have become the technology of choice in areas characterized by water scarcity thanks to RO maturity, reliability and, in the case of seawater, an abundance of the water source [12–14]. Although energy recovery systems allow substantial reductions in its energy consumption, RO still remains an energy-intensive treatment with an energy input of 2.5–7 and 0.5–3 kWh/m^3 respectively for seawater and brackish water applications [8,15]. To reduce the dependency of RO on fossil fuels and its emissions of greenhouse gasses, the concept of RE-powered RO has come forward. Table 1 summarizes the most recent review papers of such systems [12–14,16–26]. A general agreement has been found on the technological maturity of RE-powered RO. Hybrid systems that combine different REs with traditional electricity sources (e.g., grid, diesel generators) are often considered the optimal option for integration with RO. However, the intermittent and fluctuating nature of the REs still is the main technical challenge that has limited the application of RE-powered RO on a large scale. The inconsistency in the delivery of electricity by REs causes periods of low water flow through the RO membranes, thus leading to lower productivity and possibly poorer permeate quality. Membrane manufacturers and designers advise that RO should operate continuously (i.e., 24/7) and at a constant capacity (i.e., equal to the design flow rate) to maximize its performance. However, such constant capacity mode of operation is unsustainable in the long run, particularly when RE is expected to substitute fossil fuels. Energy storage solutions (e.g., batteries, supercapacitors, pumped-hydro systems) have been used by the energy and water utilities to effectively exploit the RE at its peaks of productivity [23,27,28]. Although some form of energy storage seems unavoidable in RE-powered RO [24], their installation implies more capital and maintenance costs (e.g., for large battery storage systems), as well as additional land footprint (e.g., for pumped-hydro systems). In the applications where energy storage options might be limited or not economical, it is desirable for RO to operate as a deferrable load that increases or decreases its feed flow rate as a function of RE excess power and electricity prices [29,30]. Thereby, to fully integrate RO with the availability of REs, a daily variable capacity mode of operation of the RO is an attractive option as opposed to a constant capacity operation.

Research based on modelling, laboratory and field trials on the impacts of variable capacity RO operations on water quantity, quality and membrane life is an emerging field. The current literature mostly focuses on the impacts of frequent and short-term power fluctuations caused by temporary cloud coverage or wind fluctuations, and how such oscillations in the power supply impact on water quantity and quality. As an example, [31] has demonstrated that power drops of up to 50% have a minimal influence on permeate water quality, whilst [32,33] suggest the integration of energy storage systems as adequate technologies to sustain RO performance; however, high capital costs and end-of-life disposal are identified as economic constraints to such systems. References [34–40] have investigated the performance of RO powered by solar photovoltaic (PVs) and wind energy systems that are operated either at a constant or variable capacity as a function of the available RE. The variable capacity mode is found more versatile as it allows operating RO trains independently or jointly, depending on the amount of available RE, whilst meeting the needs in terms of water quantity and quality. According to the reviewed studies, the continuous adjustment of energy consumption of a RO desalination plant to varying power generated by a wind source is feasible. Contrary to the common perception that variable operating strategy might impact on the water product quantity and quality and membrane life performances, recent studies [39,41] have demonstrated that no membrane deterioration due to excessive fouling or breakdown issues were detected during a long-term experimental study. Reference [39] found that, although the design specifications indicated optimum performance of the desalination plant at a power input of 21 kW, the experimental results showed optimum performance at a power input about 20% lower than the given design value. Although recent experimental tests have started to demonstrate the feasibility of directly connecting renewable energy sources with RO plants working at variable pressure and flow rates, such systems have not yet proven their long-term performance and economic advantage [42]. The slowness of the control system and the inertia of the desalination system in its response time to RE variations are still some of the challenges to overcome [40]. Although research on variable capacity operations of RE-powered RO plants is flourishing, the scarcity of published data on daily operations and long-term management of RE-RO plants that work with large daily flow rate variations (like, for example, the Australian desalination plants reviewed in references 43 and 44) hinders the development of daily variable capacity operations of RE-powered RO systems at a large scale [45].

Another technical challenge of using RE-powered RO is the land footprint of the REs. As an example, assuming that solar panels have a power generation capacity of 0.15 kWp/m^2 [46], the size and cost of a suitable land for a centralized PV farm to power an RO system can be quite considerable. On the other hand, an unprecedented growth of