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# Integration of reverse osmosis desalination with hybrid renewable energy sources and battery storage using electricity supply and demand-driven power pinch analysis

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ABSTRACT

This study proposes the integration of reverse osmosis desalination with renewable energy sources and battery storage using energy-efficient power pinch analysis methodology for three different scenarios under an energy management strategy considering power supply and demand and power losses of the components in the system. The power cascade table and storage cascade table are introduced as numerical tools of power pinch analysis to determine the minimum outsourced electricity supply and available excess electricity for the next day, as well as the waste electricity, needed electricity, and the battery capacity for the system during a normal operation day. An optimization algorithm was applied based on the storage cascade table for a normal operation year to determine the optimal battery capacity for a dynamic freshwater demand to minimize the outsourced freshwater. Based on the energy management strategy, a case study in London, UK, showed scenario one as the best scenario with an optimum battery capacity of 1170.36 kWh and freshwater production of 40,604.5 $m^3$, which can minimize 60,096.9 $m^3$ of outsourced freshwater with a reasonable total annual cost of 503,159 $/year.



## 1. Introduction

World energy demand is expected to increase to several times its current level over the next 50 years (Darton, 2003). RES[1] are characterized by a diversity of resources and technologies for power ranging from a few Watts to hundreds of Megawatts (Müller-Steinhagen and Nitsch, 2005). RES as solar and wind are being considered as promising power generating sources due to their availability advantages in local power generation. The limitation of solar photovoltaic technology is that it is dependent on sunlight. The availability of sunlight is geographically limited and time variant (Mal et al., 2016). Therefore, this source cannot provide a continuous supply of energy due to seasonal and periodical variations (Prasad and Natarajan, 2006). To overcome this limitation, a battery bank, which acts as a storage device electric power for maximum utilization of renewable resources can be integrated with RES to satisfy the load demand (Bajpai and Dash, 2012).

Energy storage is an issue of great importance for the development of renewable energy. At present, it is one of the greatest technical and commercial barriers due to the integration of RES, especially for those off-grid systems powered by intermittent solar or wind energy (Ma et al., 2014). Studies related to hybrid wind–photovoltaic battery power generation are mainly focused on modelling, capacity allocation, optimal design, economic evaluation, among others (Wu et al., 2015).

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**Nomenclature**

| | |
|---|---|
| AC | Alternating current |
| AOMC | Annual operating and maintenance cost |
| AEEND | Available excess electricity for the next day |
| AF | Amortization factor |
| ARC | Annual replacement cost |
| BC | Battery capacity |
| BS | Battery storage |
| CH | The charging of the battery |
| DC | Direct current |
| DCH | The discharging of the battery |
| DoD | Depth of discharge |
| $DP_{RO}$ | The power delivered to the RO system |
| EPoPA | Extended power pinch analysis |
| FOE | Feasible outsourced electricity |
| FSC | Feasible storage capacity |
| FWD | Freshwater demand |
| $FW_{RO}$ | Freshwater produced by the RO system |
| GP | RE system-generated electricity |
| IE | Infeasible electricity |
| IOE | Infeasible outsourced electricity |
| ISC | Infeasible storage capacity |
| MOES | Minimum outsourced electricity supply |
| NE | Needed electricity |
| NetAC | The net AC electricity surplus and deficit |
| OFW | Outsourced freshwater |
| PA | Pinch analysis |
| PoCA | Power cascade analysis |
| PoCT | Power cascade table |
| PoPA | Power pinch analysis |
| PV | Photovoltaic |
| RES | Renewable energy sources |
| RO | Reverse osmosis |
| SCA | Storage cascade analysis |
| SCT | Storage cascade table |
| TAC | Total annual cost |
| ACC | Total annual cost |
| TCC | Total capital cost |
| WE | Wasted electricity |

*Subscripts*

| | |
|---|---|
| i | Number of times |
| j | Number of days |

*Greek*

| | |
|---|---|
| $\delta$ | Conversion efficiency |
| $\sigma$ | Transfer efficiency |
| $\alpha$ | Self-discharge efficiency |
| $\gamma$ | Specific RO power consumption |

Remote communities are often located in areas with access to seawater or brackish groundwater. Therefore, for such communities, RO[2] desalination can be a promising solution to provide fresh water. The goal of integrating of RES with RO systems is to avoid fossil fuel dependency and minimize $CO_2$ emissions (Janghorban Esfahani and Yoo, 2016).

RO systems are known to be a cost-effective solution to produce drinkable water from underground and seawater. Hence, RO system requires less energy and maintenance than other desalination processes (Wu et al., 2015). A BS[3] system must be included to store the extra energy generated by the renewable sources functioning as a safety system.

Many researchers have focused their work on the configuration of "RES–BS" or "RES–RO". A novel model to optimize the capacity sizes of different components of hybrid solar and wind power generation systems employing a battery bank was proposed by Yang et al. (2007). Similar to Yang's work, a new methodology for calculating the optimum size of the battery bank and the PV[4] array for a standalone hybrid wind/PV system was developed by Borowy and Salameh (1996). The proposal of a power management strategy that manages the power flows of energy systems with battery to supply the load demand was conducted by Aissou et al. (2015). The feasibility of providing power and meeting load requirements of a typical commercial building using a hybrid solar–wind energy system with battery storage was assessed by Elhadidy and Shaahid (2004).

The design of reverse osmosis desalination systems with renewable energy sources was proposed by Kalogirou (2005) and Elhadidy and Shaahid (2004). The energy estimation of a stand-alone photovoltaic–wind hybrid system that is feed a large-scale by reverse osmosis desalination unit was evaluated by Cherif and Belhadj (2011).

PA[5] is powerful methodology that combines operations within a process or several process to minimize the consumption of resources and harmful emissions such as water (Hashim et al., 2013), mass, heat (Janghorban Esfahani et al., 2016), and energy (Mohammad Rozali et al., 2016). The implementation of pinch analysis with a mathematical model can provide good system design in order to determine the optimal size of the battery (Janghorban Esfahani et al., 2016), and hybrid power system (Liu et al., 2016).

The PoPA[6] has been used by many researchers who performed numerical tools of PoPA including a PoCT[7] and SCT[8] to determine the minimum amount of outsourced electricity and to optimize the size of the battery bank for a hybrid power system (Rozali et al., 2013). Ho et al. (2012) presented a new PoPA method, electric system cascade analysis, for optimizing non-intermittent power generator and energy storage in a distributed energy generation system. A novel approach called stand-alone hybrid system power pinch analysis was proposed for the design of off-grid distributed energy generation systems (Ho et al., 2013). The PoPA technique was extended for retrofitting an off-grid battery-less photovoltaic-powered reverse osmosis system with a water storage tank to minimize the required outsourced freshwater (Janghorban Esfahani and Yoo, 2016). Further, Janghorban Esfahani et al. (2015) extended the PoPA technique as EPoPA[9] for the optimal design of renewable energy systems with battery and hydrogen storage. Ho et al. (2014) extended the application of the electricity system cascade analysis (ESCA) which consists in an intermittent power source. The results showed that the ESCA had significant differences in terms of execution strategy due to intermittent power generation which was influenced by weather variability. The work also included the sizing of inverter and the optimization of a solar PV system for an isolated rural house with daily energy consumption of 5.575 kW/h.

This study modifies the off-grid battery-less PV–RO desalination system of Janghorban Esfahani and Yoo (2016) study. In order to modify the system, two renewable energy sources (solar and wind) were considered to meet the electricity demand of the RO system, while the study of Janghorban Esfahani and Yoo (2016) was modeled only for solar energy. PoPA method is applied on the system to reduce the energy losses as well as minimize outsourced freshwater consumption for three different scenarios. In order to obtain more accurate results, the energy losses is assumed to have a 95% efficiency in the converter and inverter, taking into account a lead acid-battery with charge/discharge

[2] Reverse osmosis.

[3] Battery storage.
[4] Photovoltaic.
[5] Pinch analysis.
[6] Power pinch analysis.
[7] Power cascade table.
[8] Storage cascade table.
[9] Extended power pinch analysis.