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Wind-powered desalination for strategic water storage: Techno-economic assessment of concept

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HIGHLIGHTS

- Wind-driven RO scheme was developed to create fresh water for ASR.
- A cost model was developed for estimation of the LCOW of a variable-load RO.
- Geographic feasibility analysis determined most suitable sites for wind-driven RO.
- The LCOW was estimated to be in the range of USD $ 1.57–2.11 per m^3.
- The RO's CAPEX is the most important cost component in the cost breakdown.

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ABSTRACT

Storing desalinated water within a strategic aquifer storage and recovery system has been identified as a potential cost-effective solution for the Gulf Council Cooperation (GCC) countries. In this study, we investigated a wind-driven reverse osmosis (RO) scheme to create fresh water for ASR. The ongoing Liwa ASR project in the United Arab Emirates (UAE) served as a case-study to assess the economic feasibility of the concept. As the RO plant is not destined to meet a real-time demand, its water production rate was allowed to vary, following a fluctuating wind power supply, thus avoiding the need for costly power storage. New generation wind turbines specifically designed to operate at low wind speed were investigated, which are better suited for the GCC. Sites were identified using Geographic Information System and the recently developed Wind Energy Resource Atlas of the UAE, followed by technical and cost analyses. Findings showed that the wind-driven RO scheme can be competitive with the current thermal desalination in the UAE. However, the avoidance of shut-down of a variable load RO plant hampers the effective use of the fluctuating wind power, resulting in increased plant capital costs due to plant over-sizing. Several scenarios were investigated in this regard.

1. Introduction

Long-term disruption of potable water supply is acknowledged as a serious threat to the safety and well-being of the populations around the world [1]. The risk is particularly high in water-scarce countries, such as those of the Gulf Cooperation Council (GCC). Many of the large cities in GCC countries rely almost entirely on desalination to cover their potable water demand [2,3]. It is obvious that water supply in these countries can be quite vulnerable in the case of catastrophic events such as red tide episodes or possible purposeful disruption, which may require shutting-down the desalination plants for extended periods. The risk is further exacerbated by the fact that some of the urban centers of the Middle East and North Africa (MENA) region are located far away from the sites of desalination facilities [4]. Therefore, strategic storage of sufficient quantities of fresh water, which can be made readily available, is essential to handle water demand during catastrophic or long-term supply disruptions.

Aquifer Storage and Recovery (ASR) is an emerging storage option which can be economically developed to alleviate the risk caused by such catastrophic events [1,5]. In the GCC countries, emergency water supply capacity (amount of water that meets the demand for a specific time period) in ground reservoirs and distribution systems is on the orders of single days only. Kuwait has the highest (5 days), while Qatar, Bahrain and the United Arab Emirates (UAE) have the lowest reported figure. Saudi Arabia was reported to have 3 days of emergency capacity [1].

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Symbols

C	cost
A	swept area
D	rotor diameter
E	electricity generation
E_{WT}	energy generated
f	oversize factor
FO&M	annual fixed operation and maintenance costs
H	hub height
Jw	membrane water flux
n	years of amortization
N	rotational speed of variable frequency drives
P	power
Q	water production of the plant
r	discount rate
S	salinity
V	wind speed
VO&M	variable operation and maintenance cost
λ	availability of the plant
ρ	density
Ψ	annuity factor

Abbreviations

ASR	aquifer storage and recovery
BW	brackish water
CAPEX	capital costs
CF	capacity factor
CPI	US Consumer Price Index
DASR	combination of desalination and ASR
DC	direct current
DEM	digital elevation model
ERD	energy recovery device
GCC	Gulf Council Cooperation
GIS	Geographic Information System
HPP	high pressure pump
LCOE	levelized cost of electricity
LCOW	levelized cost of water
MENA	Middle East and North Africa
O&M	operation and maintenance costs
PS	pumping stations
PX	pressure exchanger
RO	reverse osmosis
SDAWES	Seawater Desalination with an Autonomous Wind Energy System
SEC	specific energy consumption
SW	seawater
TDS	total dissolved solids
TVM	time-varying microscale
UAE	United Arab Emirates
VFD	variable frequency drive
WRF	Weather Research and Forecasting Model

Subscripts

D	direct
el	electricity
f	feed of the desalination plant
i	average hourly value
IND	indirect
max	nominal
pw	product water of the desalination plant
r	rated
t	target amount of water
WT	wind turbine

The source of stored water within an ASR system can be treated wastewater or desalinated water. Pyne & Howard [6] suggested the combination of desalination and ASR (referred to as "DASR" in the study) as a cost-effective water management technique for a brackish water reverse osmosis (BWRO) desalination plant in Corpus Christi, Texas. Implementation of the ASR, according to [6], would enable water to be stored cheaply at large capacity during the winter period [6]. Almulla et al. [5] evaluated the ASR as a storage facility with a dual purpose: to balance the annual water demand in peak months and provide a minimum of 25% stored capacity during times of emergency. Theoretically, both advanced wastewater treatment (water reclamation) and desalination can produce high quality influent that could be stored within an ASR system. According to the public view, however, desalination being a staple technology with over 60 years of commercialization is more socially acceptable to produce water compliant to potable water standards [4,7].

ASR has already been investigated for most GCC countries (Kuwait, Qatar, Oman, and Saudi Arabia). However, up to the author's knowledge, all but the UAE have not developed or are in the process of developing a strategic ASR infrastructure. The first full scale strategic water storage project in the world has been developed and is currently ongoing in the Emirate of Abu Dhabi, UAE, called the Liwa project [7]. The success of the project will potentially be a milestone for water management in arid countries worldwide. Strategic and operational water storage in the form of ASR was also tested for the Emirate of Sharjah (UAE) where an existing hybrid desalination plant would produce water for recharge in conjunction with energy generation [8].

In the present study, the concept of a wind-powered variable-load seawater desalination plant is considered for UAE, which will produce water with the aim of strategic water storage in the context of the ongoing Liwa ASR project (henceforth termed W-RO). The water produced will be pumped through pipelines to the location of the Liwa subsurface storage system, recharged into the aquifer by well injection or infiltration and ultimately recovered and sent in occasion of emergency to the large urban centers. Though previous research argues in favor of storing desalinated water as a suitable buffer for water security [6], to the author's knowledge, there has not been so far a study that deals with the utilization of a renewable-energy-powered reverse osmosis (RO) as a water supply for a strategic ASR system. The rationale behind our concept is that wind-driven RO is generally known to be one of the more cost-effective combinations of renewable energy and desalination [9,10]. For the case of a direct water supply to a community where a contracted daily (or hourly) amount of water has to be supplied, the fluctuating nature of wind resources would require the installation of either water or energy storage system at the RO plant. On the other hand, wind-powered desalination combined with strategic storage would only have to meet a long term (e.g., annual) average water production rate, equal to the aquifer's annual recharge rate, but would not be restricted over short time scales (provided the water transport system is flexible enough). Hence, the cost of water or energy storage at the RO plant would potentially be avoided, but this still has to be investigated. So, our work aims to develop a design for this type of scheme, utilizing both wind energy and variable-load RO, and to assess its viability in terms of technical feasibility as well as lifetime costs incurred in a hypothetical future implementation. The work includes identification of the optimum location of the RO plant, technical performance simulation and cost-modelling. Due to the abundance of available information on the Liwa ASR project as well as the context of the desalination industry in the UAE, an ASR-wind desalination scheme for the Emirate of Abu Dhabi was chosen as our case-study.

1.1. Concept of variable load reverse osmosis

Wind-powered RO has been tested in a number of projects worldwide, a selection of which is given in Table 1. As reviewed by Lai & Ma in 2016 [11], the solutions to mitigate the risks caused by the fluctuating