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Optimal design of stand-alone reverse osmosis desalination driven by a photovoltaic and diesel generator hybrid system

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ABSTRACT

Hybrid energy systems can be efficient alternatives for supplying potable water to and satisfying the electrical loads of remote areas. The objective of this article is to optimize the size of a reverse osmosis desalination-based diesel and photovoltaic power plant for increasing fresh water availability and meeting the electrical load demand of a stand-alone region in Iran. The size of the battery bank, the area of the photovoltaic system, and the fuel consumption of the diesel generator within the proposed hybrid system are optimized so as to minimize the life cycle cost of the system. For this aim, a power management strategy is designed, and an efficient metaheuristic technique based on tabu search is used. The results are compared with those obtained by harmony search and simulated annealing algorithms. Furthermore, the effects of varying fuel cost, interest rate, photovoltaic initial cost, and battery initial cost on the economic parameters of the hybrid system are also discussed. From the results it is seen that the photovoltaic/diesel/battery/reverse osmosis desalination system is economically and environmentally advantageous to a single diesel system or a single photovoltaic system for the investigated region. Moreover, tabu search provides more promising results than the other investigated algorithms.

1. Introduction

Water and energy are essential resources for societies and their development. Of the world's water, about 97% is saltwater and 3% fresh water. Over 1.5 billion people globally lack access to grid electricity, mostly in small remote villages which are isolated from utilities (Ma et al., 2014). Approximately one quarter of the global population lacks access to adequate amounts of fresh water (Koutroulis and Kolokotsa, 2010), fresh water scarcity is increasingly problematic in many areas of the world (He et al., 2015). Water desalination is a viable technology for the provision of potable water (Shannon et al., 2008), but its use is impeded due to high economic costs, mainly linked to its energy intensiveness (Fritzmann et al., 2007). Furthermore, the current use of fossil fuels to drive desalination, often via diesel generators, contributes to climate change, highlighting the importance of reducing its greenhouse gas emissions (Subramani et al., 2011).

Water desalination is currently mainly based on reverse osmosis (RO), which exhibits relatively low energy requirements and costs (Spyrou and Anagnostopoulos, 2010). Needing only electricity, RO use renewable energy technologies such as photovoltaics (PV) (Garcí, 2003). The application of renewable energy for reverse osmosis desalination (ROD) is particularly beneficial in remote locations (Koroneos et al., 2007). Furthermore, some researchers have demonstrated that desalination driven by hybrid energy systems (HESs) can provide advantageous options for remote and small communities in mainland regions and small coastal cities and towns. In HESs, optimal sizing is vital to achieve a reliable and cost-effective generation system.

The optimization of desalination systems driven by HESs can enhance their cost-effectiveness and reliability. An important advantage of such a desalination system is the ability to be applied on small scales. The electricity from photovoltaic collectors with battery (BAT) storage systems can be used to drive high-pressure pumps in reverse osmosis plants. A diesel generator (DG) typically acts as a backup power supply for periods when the demand is high.

RO desalination using numerous energy supply combinations have been reported, sometimes using renewable energy. Some investigated systems in the literature are presented in Table 1.

He et al. (2015) proposed a RO seawater desalination plant driven by PV and pressure-retarded osmosis, and examined the feasibility of two schemes: salinity-solar driven RO operation and salinity driven RO operation. Al Malki et al. (1998) integrated renewable energy (solar and wind) to an RO system for desalinating brackish water and

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Nomenclature

A_{PV} total area occupied by the set of photovoltaic (PV) panels (m^2)
A_{DG}, B_{DG} coefficients of the consumption curve (L/kWh)
$Batt_S(t-1)$, $Batt_S(t)$ charge levels of the battery system at times $t-1$ and t (kWh)
$Batt_{S\text{-min}}$ minimum charge of the storage system (kWh)
$Batt_{S\text{-max}}$ maximum charge of the storage system (kWh)
C_F hourly cost of fuel consumption ($)
CD_F total cost of fuel consumption ($)
CC capital cost ($)
CRF capital recovery factor
C_{PV} unit cost of PV panel system ($/$m^2$)
$C_{Mnt\text{-}PV}$ annual operation and maintenance cost of PV system ($/$m^2$/year)
C_{BAT} battery cost ($)
$C_{Mnt\text{-}BAT}$ annual maintenance cost of battery ($/year)
CINV converter/inverter price ($)
CMnt-INV annual maintenance cost of converter/inverter ($/year)
C_{DG} diesel generator (DG) cost ($)
$C_{Mnt\text{-}DG}$ annual maintenance cost of DG ($/year)
$C_{HM\text{-}DG}$ hourly maintenance cost of DG ($/h)
Ca_{WD} reverse osmosis desalination (ROD) system volumetric daily capacity (m^3/day)
CROD daily cost of RO system per unit (m^3) capacity of the desalinated water of RO system ($/$m^3$/day)
CMnt-ROD maintenance cost of RO system ($/$m^3$)
C_{WTa} water tank cost ($/$m^3$)
C_{MR} membrane replacement cost ($/$m^3$)
C_{CH} cost of chemicals ($/$m^3$)
CDWP cost of the desalinated water produced ($/$m^3$)
D_{WC} desalination water production capacity per day (m^3/day)
D_{WD} total daily volumetric fresh water demand (m^3/day)
DOD maximum depth of discharge (%)
ED_l energy demand (kWh)
E_G generated energy by PV panels (kWh)
F_{DG} fuel consumption of DG (L/h)
F_R annual fuel required (L/year)
H_{WD} hourly volumetric water demand (m^3/h)
i interest rate (%)
iter iteration index
LCC life cycle cost ($)
LCOE levelized cost of energy ($/kWh)
MC maintenance cost ($)
NOCT normal operating cell temperature (°C)
n project lifetime (year)
N_{BAT} number of batteries
N_{DG} number of diesel generators
N_{Me} number of membrane replacements per year
n_{trial} trial solutions
P_{PV} output electrical power of PV panels (kW)
P_{DG} output power of DG (kW)
$P_{R\text{-}DG}$ rated power of DG (kW)
P_{fuel} hourly cost of fuel consumption ($/L)
P_{DEM} desalination electric power (kW)
P_{DI} ROD unit nominal load (kW)
P_{DES} instantaneous power utilization of ROD unit (kW)
P_{MD} ROD unit minimum load (kW)
PR-CDG diesel continuous power (kW)
P_{INV} nominal converter/inverter power (kW)
P_D desalination installed power (kW)
PW_{BAT} present worth of battery
PW_{DG} present worth of one diesel generator
P_{fuel} fuel cost ($/L)
R_t solar irradiance (kW/m^2)
S_{DC} desalination energy consumption (kWh/m^3)
S_{BAT} nominal capacity of battery bank (kWh)
T_{ref} cell temperature at reference conditions (°C)
T_{air} ambient temperature (°C)
TC_{MR} membrane replacement cost of ROD unit ($)
TC_{CH} cost of chemicals of ROD unit ($)
V_{WTa} fresh water tank volumetric capacity (m^3)
$x_{initial}$ initial random solution
$x_{current}$ current solution
x_{best} best solution
x_{trial} each trial solution
β_T temperature coefficient of PV panel (°C^{-1})
σ hourly self-discharge rate (%)
η_{PV} PV panel reference efficiency (%)
η_{pc} power conditioning efficiency (%)
η_r reference module efficiency (%)
ηINV inverter efficiency (%)
η_{bf} discharging efficiency of battery bank (%)
η_{bc} charge efficiency of battery bank (%)

Table 1
Literature review.

Authors/year	PV	wind	BAT	DG	RO	Other	Method
de la Nuez et al. (2004)	–	✓	–	–	✓	–	Simulation
Koklas and Papathanassiou (2006)	–	✓	✓	–	✓	–	Simulation
Tzen and Morris (2003)	–	✓	✓	–	✓	–	–
Helal et al. (2008)	✓	–	–	✓	✓	–	Simulation
Joyce et al. (2001)	✓	–	–	–	✓	–	Experimental
Ahmad et al. (2015)	✓	–	–	–	✓	–	Experimental
Jones et al. (2016)	✓	–	–	–	✓	✓	Simulation
Masson et al. (2005)	✓	–	–	–	✓	–	Simulation
Clarke et al. (2013)	✓	–	✓/-	–	✓	–	Experimental/simulation MATLAB
Novosel et al. (2015)	✓	✓	–	–	✓	✓	EnergyPLAN
Setiawan et al. (2009)	✓	✓	✓	✓	✓	–	HOMER
Voivontas et al. (2001)	✓	✓	–	–	✓	✓	Software application
Clarke et al. (2015)	✓	–	✓		✓	✓	PSO; HOMER
Bourouni et al. (2011)	✓	✓	✓	–	✓	–	Genetic algorithm (GA)
Qiblawey et al. (2011)	✓	–	✓	–	✓	–	Simulation; software EnviroMon
MOkheimer et al. (2013)	✓	✓	✓	–	✓	–	MATLAB software Package
Hossam-Eldin et al. (2012)	✓	✓	✓	✓	✓	–	Simulation; optimization program
Cherif and Belhadj (2011)	✓	✓	–	–	✓	–	Simulation; software