Size optimization of a hybrid PV/wind/diesel/battery power system for reverse osmosis desalination
Daming Xu, Tom Acker and Xuhui Zhang

ABSTRACT

This study was to find the optimal configuration for an independent renewable energy system for reverse osmosis (RO) desalination. The objective was to find the lowest levelized cost of energy (LCOE), with power reliability as the constraint. A genetic algorithm was used to solve the nonlinear integer programming program. A site with brackish groundwater in Arizona, USA was selected. The capacity of the RO system was 18.93 m³/d (5,000 gal/d), requiring a constant power consumption of 3.95 kW. Two scenarios were considered in terms of diesel generator (DG) allowed running time. The results showed that the optimal configuration was a hybrid photovoltaic/wind/diesel/battery system with 0.56 USD/kWh and the corresponding levelized cost of water 3.84 USD/m³, when the DG can run in any hour every day. The optimal solution was a hybrid wind/photovoltaic/battery system with 0.69 USD/kWh and 4.48 USD/m³, when the DG can run between 9 am and 9 pm every day for noise control. Both the two LCOWs were about half of the 7.9 USD/m³ currently paid by residents that live in the area. Sensitivity analyses showed the LCOE was fairly insensitive to photovoltaic panel tilt angle over a range for both the two configurations.

Key words | brackish water desalination, genetic algorithm, optimal sizing, renewable energy, reverse osmosis

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_i$</td>
<td>index of anisotropy</td>
</tr>
<tr>
<td>$D_{WD}$</td>
<td>daily volumetric fresh water demand (m³)</td>
</tr>
<tr>
<td>$E_{batt,t}$</td>
<td>energy stored in the battery bank at the end of hour $t$ (kWh)</td>
</tr>
<tr>
<td>$E_{batt,rated}$</td>
<td>energy stored in the battery bank when at rated capacity (kWh)</td>
</tr>
<tr>
<td>$E_{DG,t}$</td>
<td>energy generated by the diesel generator (kWh)</td>
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<tr>
<td>$E_{gen,t}$</td>
<td>energy generated for hour $t$ (kWh)</td>
</tr>
<tr>
<td>$E_{load,t}$</td>
<td>load demand for hour $t$ (kW)</td>
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<tr>
<td>$E_j$</td>
<td>electricity generation in year $j$ (kWh)</td>
</tr>
<tr>
<td>$E_{PV,j}$</td>
<td>energy generated by the photovoltaic panel (kWh)</td>
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<tr>
<td>$E_{WTG,t}$</td>
<td>energy generated by the wind turbine generator (kWh)</td>
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<tr>
<td>$f$</td>
<td>modulating factor</td>
</tr>
<tr>
<td>$F_{P,j}$</td>
<td>fuel expenditures of the renewable energy system in year $j$ (USD)</td>
</tr>
<tr>
<td>$G$</td>
<td>mean global horizontal irradiance (W/m²)</td>
</tr>
<tr>
<td>$G_B$</td>
<td>direct beam part of the mean global horizontal irradiance (W/m²)</td>
</tr>
<tr>
<td>$G_D$</td>
<td>diffuse part of the mean global horizontal irradiance (W/m²)</td>
</tr>
<tr>
<td>$G_O$</td>
<td>average extraterrestrial irradiance at the top of the earth’s atmosphere (W/m²)</td>
</tr>
<tr>
<td>$G_{ref}$</td>
<td>irradiance under reference operating conditions, 1,000 W/m²</td>
</tr>
<tr>
<td>$G_T$</td>
<td>hourly incident irradiance on the tilted photovoltaic panel surface (W/m²)</td>
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USA
\( H_{WD} \) hourly volumetric water demand of the reverse osmosis system (m³/h)
\( H \) height (m)
\( I_{RO,j} \) reverse osmosis system investment expenditures in year \( j \) (including financing) (USD)
\( I_{MP} \) maximum power point current of a photovoltaic panel (A)
\( I_{MP,\text{ref}} \) \( I_{MP} \) under reference operating conditions (A)
\( I_{PV,j} \) renewable energy system investment expenditures in year \( j \) (including financing) (USD)
\( I_{SC,\text{ref}} \) short circuit current under reference operating conditions (A)
\( I_{\text{tank},j} \) investment expenditures in the tank in year \( j \) (including financing) (USD)
\( j \) year \( j \)
\( L_{\text{ind}} \) the number of decision variables that define an individual
\( LPSP_{\text{set}} \) loss of power supply probability set value
\( M_{RO,j} \) operations and maintenance expenditures for the reverse osmosis system in year \( j \) (USD)
\( M_{P,j} \) operations and maintenance expenditures for the renewable system in year \( j \) (USD)
\( M_{\text{tank},j} \) operations and maintenance expenditures for the tank in year \( j \) (USD)
\( n \) analysis period (year)
\( N_{\text{batt}} \) number of batteries in the battery bank
\( N_{\text{batt,p}} \) number of battery strings parallel
\( N_{\text{batt,s}} \) number of batteries in a string
\( N_{\text{iter}} \) number of generations
\( N_{\text{ind}} \) number of individuals in a population
\( N_{\text{PV}} \) number of photovoltaic panels
\( N_{\text{PV,p}} \) number of strings of photovoltaic panels in parallel
\( N_{\text{PV,s}} \) number of photovoltaic panels in a string
\( N_{\text{WTG}} \) number of wind turbine generators
\( P_{\text{DEM}} \) electric power required for desalination (kW)
\( P_{MP} \) photovoltaic panel maximum power point power (W)
\( Q_{\text{lifetime}} \) battery lifetime energy throughput (Ah)
\( Q_{\text{thrpt}} \) battery bank annual energy throughput (Ah)
\( Q_{W,j} \) water production in year \( j \) (m³)
\( r \) discount rate
\( R_{\text{cro}} \) crossover rate
\( R_{B} \) beam radiation ratio: incident radiation on a tilted surface divided by that on a horizontal surface
\( R_{\text{batt}} \) life of the battery (year)
\( R_{\text{batt,f}} \) battery float life (year)
\( R_{\text{mut}} \) mutation rate
\( S_{DC} \) average specific energy consumption for desalination (kWh/m³)
\( SOC_{\text{start}} \) state of charge set point to start diesel generators
\( T_{C} \) operating temperature of the photovoltaic panel (°C)
\( T_{C,\text{ref}} \) photovoltaic panel temperature of 25 °C under reference operating conditions
\( TYPE_{\text{WTG}} \) type of wind turbine generators
\( V_{k} \) wind speed at height \( k \) (Hk) (m/s)
\( V_{MP} \) photovoltaic panel voltage at maximum power point (V)
\( V_{MP,\text{ref}} \) \( V_{MP} \) under reference operating conditions (V)
\( V_{\text{tank}} \) fresh water tank volumetric capacity (m³)
\( \alpha \) surface roughness factor
\( \beta \) photovoltaic panel tilt angle (degree)
\( \eta_{\text{ch,batt}} \) battery charging efficiency
\( \eta_{\text{disch,batt}} \) battery discharging efficiency
\( \eta_{\text{inv,bi}} \) bidirectional converter efficiency when as an inverter
\( \eta_{\text{inv,soalr}} \) efficiency of the solar inverter
\( \eta_{\text{inv,wind}} \) efficiency of the wind inverter
\( \eta_{\text{rect,bi}} \) bidirectional converter efficiency when as a rectifier
\( \mu_{\text{Lsc}} \) short circuit current temperature coefficient (A/°C)
\( \mu_{V,\text{oc}} \) open circuit voltage temperature coefficient (V/°C)
\( \rho_{G} \) ground reflectance
\( \sigma \) battery hourly self-discharge rate
\( AC \) alternating current
\( Ah \) Ampere-hour
\( DG \) diesel generator
\( DOD \) depth of discharge
\( GA \) genetic algorithm
\( IEA \) International Energy Agency
\( LCOE \) levelized cost of energy
\( LPS \) loss of power supply
INTRODUCTION

Access to affordable, reliable electricity and clean drinking water remain as two of the greatest challenges facing society. In 2015 the World Health Organization estimated that more than 840 million people worldwide lacked drinkable water, and that an additional 260 million had limited access, spending more than half an hour per day to collect water from an improved source (Gude et al. 2018; WHO 2017). Shannon et al. (2013) reported that 97.5% of all water resources on the Earth are saline, in the oceans and saline aquifers, and therefore harnessing desalination to clean water could have a dramatic effect on addressing water scarcity. With regard to electricity, the International Energy Agency (IEA) reported that in 2016 the number of people lacking access to electricity exceeded one billion (IEA 2017). Geographically, the preponderance of these people live in the same developing areas of the world where water scarcity is an issue.

The IEA further reported that although the majority of areas electrified since 2000 came through connections to the electricity grid, since 2012 34% of new connections had electricity provided by renewable energy (RE) sources, and that off-grid and mini-grid systems were implemented in 6% of the cases. They go on to project that by 2030, over 60% of new electricity access will be provided by renewable energy sources, and that off-grid and mini-grid systems will provide about half of the new access (IEA 2017). The implication here is that as future water development occurs, it will frequently be coupled to renewable energy systems.

There are numerous technologies for desalinating water, all of which use thermal energy, electrical energy or a combination. Multiple effect distillation, thermal vapor compression, mechanical vapor compression, multistage flash distillation and solar distillation are examples of techniques that rely primarily on thermal energy to evaporate water, and are therefore quite energy intensive (Veerapaneni et al. 2014). For brackish water resources that have lower total dissolved solids (TDS) (1,000 mg/L < TDS < 10,000 mg/L) than seawater (>35,000 mg/L), pressure-driven membrane technologies such as reverse osmosis (RO), nanofiltration, and electrodialysis are practical, since the energy required to desalinate drops significantly with TDS level. Other processes combine both thermal and membrane separation techniques to form hybrid methods, as is the case with membrane distillation systems (Gude & Nirmalakhandan 2010; Gude 2016).

In the past two decades, desalination technologies have been improved and costs have decreased. Desalination is currently growing at a significant combined annual growth rate of 7.4%, with RO as the dominant technology accounting for about 70% of installations, according to data obtained for the IDA’s 27th Desalination Inventory, compiled by Global Water Intelligence (Filtration + Separation). In rural areas with brackish water where renewable energy resources exist, RO desalination is a good choice for water desalination (Al-Karaghouli et al. 2019; Charcosset 2009; Shatat et al. 2013; Abdelkareem et al. 2018).

With the need for rural development of both electricity and potable water resources, and with the emergence of renewable energy as cost competitive at off-grid sites and with some instances of grid extension, it is important to study renewable energy powered desalination. Several recent publications have reviewed renewable energy powered desalination, pointing out the advantages and challenges of employing renewable energy (Abdelkareem et al. 2018; Ali et al. 2018; Giwa & Hasan 2018; Khan et al. 2018; Zhang et al. 2018; Freire-Gormaly & Bilton 2019). Gude & Nirmalakhandan (2010) made the point that desalinating brackish water sources with renewable energy in rural regions represent ‘rational and logical approaches’. However, as Mathioulakis et al. (2007) indicated, a major
problem exists in the optimal economic design of renewable-energy powered desalination plants, especially in remote or arid areas.

The Southwest Navajo Nation (SNN) is a rural area in northeastern Arizona, USA, which has a large amount of accessible brackish groundwater with poor water quality (Androwski et al. 2014). The SNN has about 12,000 residents, who haul potable water, averaging 0.38 m³ (100 gal) per capita for household and livestock use. In transporting this water, residents drive an average of 48 km per day, and costs are 3 to 10 USD per 0.38 m³ of potable water (Haws 2014). As a reference, this rate is approximately ten times what people in Flagstaff, Arizona pay for water, 0.385 USD per 0.38 m³ (City of Flagstaff). Arizona is known to have a good solar resource across the entire state, and this includes the SNN (Dunlap et al. 1994). The Navajo Nation, in consultation with the US Bureau of Reclamation, has made the decision to develop a desalination system powered by renewable energy at Leupp, Coconino County, Arizona (35.431°N, 111.112°W), where brine pumped water physical condition is 1,000 mg/L of dissolved minerals.

A fresh water production of 18.93 m³/d (5,000 gal/d) RO was chosen. The objective of this work, therefore, was to find the optimal, least cost, configuration for a renewable energy reverse osmosis desalination (REROD) system based on a genetic algorithm (GA). Two scenarios according to diesel generator (DG) allowed running time were considered.

PROBLEM FORMULATIONS

The renewable energy reverse osmosis desalination system topology

Figure 1 shows a schematic of the studied REROD system. The system consists of two main parts: an RE system and an RO system. In the present study, the capacity of the RO system was a design condition, with a required output of clean water of 18.93 m³/d. Consistent with recommended practice, the electric power consumption of the RO system was assumed to be constant (Gude 2018), and the system was not permitted to be dispatched below its full output and was required to stay operating at all times, except when out of service for maintenance. Thus, the focus of this study was the optimal sizing of the RE system instead of the entire REROD system.

The RE system was built upon an alternating current (AC) bus. The voltage and frequency stability depends upon one DG and a cluster of bi-directional converters connected to a battery bank. The cluster of bi-directional

![Figure 1](https://iwaponline.com/jwrd/article-pdf/9/4/405/628993/jwrd0090405.pdf)
converting is the central control unit, which dispatches the
diesel power generation through a signal cable connection.
The solar and wind power generation are connected to the
AC bus via inverters, and the RO system gets its power
supply from the AC bus.

Optimization of the RE system was broken down into
three distinct activities (Farret & Simões 2006):
1. Simulation of RE system operation – for each candidate
RE system, the performance of the entire system and
each of its components in serving the RO system load is
simulated. In the genetic algorithm to be described
later, only those RE systems that can adequately serve
the system load are considered in the optimization.
2. Optimization – use a genetic algorithm to select the best
RE system design from the many possible alternatives
based upon the objective function of minimizing the leve-
lized cost of energy (LCOE).
3. Sensitivity analysis – once an optimal design is identified,
perform a sensitivity analysis to determine how sensitive
the LCOE is to changes in input parameters.

The first task undertaken to perform the optimization
was to create a simulation of the RE system performance.
As shown in Figure 1, the RE system may be composed of
combinations of the following components: solar PV
panels, WTGs, one DG, and/or battery energy storage
(batt). To perform the simulation, it was necessary to build
mathematical models of each RE system component and
the load, which is the RO system power consumption. In
the section that follows, the RE system models are
described.

Models employed in the REROD system simulation

Solar energy conversion related models

*Hay-Davies-Klucher-Reindl model.* It is necessary to com-
pute the solar radiation incident on a tilted surface using
the known radiation on a horizontal surface. The tilted sur-
face total solar radiation consists of beam radiation and
diffuse radiation from the sky and ground-reflected radia-
tion. The diffuse radiation is the sum of three com-
ponents: circumsolar and isotropic diffuse and horizon
brightening. The Hay-Davies-Klucher-Reindl anisotropic
model (Duffie & Beckman 2013) was used to compute the
total hourly incident irradiance on a tilted PV panel surface,
$G_T$, in W/m²:

$$
G_T = (G_B + G_D A_i) R_B + G_D (1 - A_i) \left( \frac{1 - \cos(\beta)}{2} \right) 
\times \left[ 1 + f \sin^3 \left( \frac{\beta}{2} \right) \right] + G_{DG} \left( \frac{1 - \cos(\beta)}{2} \right)
$$

where, $A_i = G_B / G_O$, and is a function of the atmosphere
transmittance regarding beam radiation.

*Photovoltaic panel electric power conversion model.* With
the total hourly incident irradiance on a tilted PV panel sur-
face known, it is next necessary to compute PV panel
average hourly output power. The computational model
given by Lasnier & Gan (1990) was used, which defines the
current–voltage relationships based on PV panel electrical
characteristics. The effects of radiation level and panel
temperature upon output power are considered. The output power $P_{MP}$ from a PV panel with maximum power
point tracking is given as:

$$\begin{cases} 
P_{MP} = V_{MP} I_{MP} \\
V_{MP} = V_{MP, ref} + \mu_{V, oc}(T_C - T_{C, ref}) \\
I_{MP} = I_{MP, ref} + I_{SC, ref} \left( \frac{G_T}{G_{ref}} \right) + \mu_{I, sc}(T_C - T_{C, ref})
\end{cases}
$$

2. Wind turbine generator models

Due to the high dependence of wind power on the wind
speed, and because the wind speed data available were not
at the turbine hub height, the hub height wind speed was cal-
culated using the following power–law relationship (Borowy
& Salameh 1996):

$$V_2 = \left( \frac{H_2}{H_1} \right)^{\alpha} V_1
$$

Because the terrain is relatively flat and there is not
much vegetation, a $1/7$th power law boundary layer profile
similar to turbulent flow over a flat plate was selected.

With an estimate of the hub height wind speed now
known, the power output of a WTG can be calculated
using its experimentally verified power curve. The power curve maps the power output to the hub height wind speed. The Tumo-Int series WTGs were considered in this work as typical of small turbines currently available on the market (Tumo Int Corporation Limited). Turbines with rated power outputs of 1 KW, 2 KW, and 3 KW were coded as types I, II, and III. Their power curves are shown in Figure 2.

**Diesel generator models**

In order to provide continuous power to the RO system in this off-grid system, the wind and/or PV power needs to be coupled with a combustion engine, batteries, or both. For this study, the combustion engine selected was a Cummins SD 7.5 kW/60 Hz commercial mobile diesel generator [Commercial Mobile | Cummins Inc. (n.d.)]. The engine’s output power-fuel curve, drawn with least-squares fitting method shown in Figure 3, was used to calculate the diesel fuel consumption.

The filters, which are for diesel oil, air, and lubricant, need replacement every 500 working hours (Emergency Power). The DG was set to run at 50%–75% of its rated power for fuel efficiency and mechanical health. When use of a DG was required, the RO system power consumption was about 50% of the DG rated power, thus guaranteeing a minimum DG load rate. In the simulation, the DG could be set to turn on when the battery state of charge (SOC) falls below a threshold, as will be described in a following subsection.

**Models of lead acid batteries**

Due to their long history of use and well-understood cost and maintenance characteristics, lead-acid batteries were selected for this study. To calculate battery lifetime, the Ampere-hour (Ah) counting model (Farret & Simões 2006) was used. The depth of discharge (DOD)-cycles to failure relations for general valve regulated lead acid (VRLA) batteries were chosen. Figure 4 shows the VRLA battery lifetime curves (Wust 2012).
The DOD is the absolute discharge relative to the rated cell capacity, which is assumed to remain unchanged as it ages (Drouilhet & Johnson 1997). For the Ah counting model, battery lifetime Ah throughput is obtained by multiplying the lifetime throughput coefficient and the rated Ah capacity. This model is employed in the commercially available renewable energy off-grid optimization software HOMER, in which there is an assumption that DOD does not affect the lifetime throughput. In the present work, the mean lifetime Ah throughput is the mean lifetime throughput coefficient multiplied by the rated Ah capacity. The battery bank lifetime is given as:

$$R_{batt} = \min \left( \frac{N_{batt} Q_{litetime}}{Q_{thrpt}}, R_{batt,i} \right)$$

VRLA 200 Ah, 2 V batteries were used, with 24 batteries connected in one string, summing to 48 V per string. The mean lifetime throughput coefficient of the batteries was 587.5, thus the VRLA battery mean lifetime Ah throughput was 587.5 × 200 = 117,500 Ah. The batteries have a round-trip efficiency of 0.85 (HOMER) and the DOD was set as 50% to avoid deep discharge which harms the batteries and shortens their lives.

**The power conditioning equipment models**

Solar and wind inverters and bi-directional converters play a crucial role in renewable energy systems. A solar or wind inverter’s basic function is to ‘invert’ the direct current output into alternating current, in addition to other functions such as maximum power point tracking, data monitoring and protection, etc. A bi-directional converter’s basic functions are as a rectifier or an inverter, in addition to other functions as battery management, generator management, load shedding, etc.

The solar inverters, wind inverters, and bi-directional converters were modeled using conversion efficiencies. The bi-directional converter working efficiency depends on its role as a rectifier or an inverter. The specific equipment selected for use in this off-grid system will be described later.

**Modeling of RO desalination**

The electric power required for desalination $P_{DEM}$ is affected by the hourly volumetric water demand $H_{WD}$ of the RO system and the mean specific energy consumption for desalination $S_{DC}$ (Maleki 2018):

$$P_{DEM} = H_{WD} S_{DC}$$

The average energy consumption for RO system technology ranges from 3.7 to 8 kWh/m³, and generally the smaller the size the higher the power consumption (Al-Karagholi & Kazmerski 2013). The power consumption was set at 5 kWh/m³ for the RO desalination unit, given the brackish water quality available at the site (Gude 2018), and including the well pump and energy recovery devices.

Traditionally, desalination systems are designed to operate with a constant power input. Usually, an unstable power input makes the desalination system operate in non-optimal conditions and this may cause severe operational problems. For example, due to power supply variation, frequent starting and stopping and partial load operation can lead to scaling, fouling, and unpredictable phenomena of membranes in RO systems (Gude 2018). The RO equipment capacity was selected as 18.93 m³/d according to the fresh water demand, and the RO system is assumed to work at its constant and rated electric load. Under these conditions, the $H_{WD}$ is 0.79 m³/h and the hourly average power consumption is 3.95 kW.

In the RO system the fresh water tank volumetric capacity is proportional to the daily fresh water demand $D_{WD}$. To ensure desalination system autonomy, 2 days’ storage period was chosen (Maleki 2018), so the fresh water tank volume $V_{tank}$ is

$$V_{tank} = 2D_{WD}$$

**The RE system operation simulation**

The logistic model and the time series method (Manwell et al. 2006) were used for the simulation. Logistical models are employed for long-term performance predictions and system sizing. Within each time step of the simulation, an energy balance approach is adopted where energy is conserved at each time step and throughout the entire simulation.

The simulation period was 1 year and the time step was 1 hour. During each time step, the solar, wind and diesel energy and load were assumed to be constant. The energy...
generated by the WTGs, PV panels, and the DG for hour \( t \), \( E_{\text{gen},t} \), is expressed as:

\[
E_{\text{gen},t} = N_{\text{WTG}} E_{\text{WTG},t} \eta_{\text{inv,wind}} + N_{\text{PV}} E_{\text{PV},t} \eta_{\text{inv,solar}} + E_{\text{DG},t}
\]  

(7)

If the energy generated from the PV panels, WTGs, and the DG exceeds that of the RO load demand, the battery bank will be charged. Thus, if charging, at the end of hour \( t \):

\[
E_{\text{batt},t} = E_{\text{batt},t-1}(1 - \sigma) + (E_{\text{gen},t} - E_{\text{load},t}) \eta_{\text{rect,bi}} \eta_{\text{ch,batt}}
\]

(8)

If the load demand is greater than the energy generated, then the battery bank will be discharged with the amount to cover the deficit. At the end of hour \( t \), if discharging, the energy stored in the battery bank is given by:

\[
E_{\text{batt},t} = E_{\text{batt},t-1}(1 - \sigma) - (E_{\text{load},t} - E_{\text{gen},t}) / (\eta_{\text{disch,batt}} \eta_{\text{inv,bi}})
\]

(9)

### System dispatch and power reliability

In order to supply the electrical load, the power resources were dispatched in the following order (Xu & Kang 2015):

1. the WTGs and PV panels
2. the batteries
3. the DG.

The micro-cycling dispatch strategy (Bernal-Agustín & Dufo-López 2009) was employed. The generator starts when the battery SOC drops to a defined SOC set point (SOC\(_{\text{start}}\)), and stops if the renewable energy production plus the battery bank can cover the load. The SOC\(_{\text{start}}\) is determined based upon a defined permissible DOD, as follows:

\[
\text{SOC}_{\text{start}} = 1 - \text{DOD}
\]

(10)

Generally, DOD = 0.5 is safe for VRLA batteries’ lifetime. The batteries’ SOC at the end of hour \( t \) SOC\(_{t}\) is:

\[
\text{SOC}_{t} = \frac{E_{\text{batt},t}}{E_{\text{batt,rated}}}
\]

(11)

Ideally, the battery bank is recharged from renewable energy as much as possible. However, if at the beginning of a time step the SOC\(_{t} < \text{SOC}_{\text{start}}\), then the DGs are instructed to start and produce power for the hour. In the next time step, if renewable energy plus the battery bank covers the load and SOC\(_{t} > \text{SOC}_{\text{start}}\), then the DGs stop; otherwise, the DGs keep running. When the SOC\(_{t} = 1\), and if there is excess renewable energy, the renewable power generation will be constrained.

If there is not a DG in any particular configuration of the hybrid power system being simulated, then any unmet electric load demand must be recorded, and there will be no water production because the RO system shuts down. When the generated energy plus that stored in the batteries is insufficient to satisfy the load demand for hour \( t \), that deficit is tabulated as the ‘loss of power supply’ (LPS) for hour \( t \), and can be expressed as:

\[
\text{LPS}_{t} = \frac{E_{\text{load},t} - (E_{\text{gen},t} + E_{\text{batt},t} - E_{\text{batt,rated}}) \eta_{\text{disch,batt}} \eta_{\text{inv,bi}})}{E_{\text{load},t}}
\]

(12)

The loss of power supply probability (LPSP) over the period of the simulation, \( T \), for example, over the course of a year, is the ratio of the sum of LPSP values to the sum of the electric load demand throughout that period, as defined by (Borowy & Salameh 1996):

\[
\text{LPSP} = \frac{\sum_{t=1}^{T} \text{LPS}_{t}}{\sum_{t=1}^{T} E_{\text{load},t}}
\]

(13)

The LPSP is the power reliability index of the RE system. The power reliability can be guaranteed when a DG is in the power system (assuming the fuel tank for the DG is appropriately sized), while it cannot necessarily be guaranteed in a pure renewable energy system. Because the RO system needs to work at a constant rated load and because it is desirable to run the RO continuously between its maintenance intervals (no shut downs), any power system configuration with an LPSP > 0 was discarded as an infeasible solution.

### Cost functions

The LCOE calculation method used by the US Department of Energy (Levelized Cost of Energy (US Department of Energy)) was employed for the RE system:

\[
\text{LCOE} = \sum_{j=1}^{n} I_{P_j} + M_{P_j} + F_{P_j} \frac{\sum_{j=1}^{n} E_{j}}{(1 + r)^j}
\]

(14)
where \( I_p, M_p, \) and \( F_p \) represent the investment, maintenance and operations (M&O), and fuel costs of the RE system, \( E \) is the energy produced, and \( r \) is the discount rate. Table 1 lists the items considered in the LCOE analysis of the RE system. When equipment replacements occur, the investment expenditures are used in that year.

Following the definition of LCOE presented above, the levelized cost of water (LCOW) is defined below, which could also be employed as the cost function for the REROD system:

\[
LCOW = \frac{\left( I_{pj} + M_{pj} + F_{pj} \right) + \left( I_{RO,j} + M_{RO,j} \right) + \left( I_{tank,j} + M_{tank,j} \right)}{(1+r)^j} \sum_{j=1}^{n} \frac{Q_{w,j}}{C_{30}}
\]  

Note \( Q_W \) is the annual quantity of water produced over the analysis period, and that the RO system life cycle cost, as indicated by the LCOW, is an annualized cost that takes into consideration the time value of money. It is similar to the LCOE but includes the RO system and tank capital cost and their operation and maintenance cost. The RO system operation and maintenance cost includes its maintenance cost, the membrane replacement cost, and chemicals costs (Maleki 2018).

As the capacity and electric power consumption of the RO system can be predetermined and is unchanging because the output is assumed constant (no dispatch), the optimal sizing of the RE system was studied instead of the entire REROD system. Therefore, the LCOE was adopted as the objective function in sizing the RE system. The LCOW is also an important index in terms of desalination.

### Optimization problem formulation

The optimal sizing of the RE systems was formulated as a single criterion integer programming as:

\[
\begin{align*}
\min & \quad LCOE \\
\text{s.t.} & \quad \text{LPSP} \leq \text{LPSP}_{\text{set}} \\
& \quad \beta = 0^\circ, 1^\circ, 2^\circ, \cdots, 90^\circ \\
& \quad N_{\text{PV,p}} = 0, 1, 2, \cdots, 100 \\
& \quad N_{\text{batt,p}} = 0, 1, 2, \cdots, 50 \\
& \quad N_{\text{DG}} = 0, 1
\end{align*}
\]  

where:

\[
\begin{align*}
N_{\text{PV}} &= N_{\text{PV,s}} N_{\text{PV,p}} \\
N_{\text{batt}} &= N_{\text{batt,s}} N_{\text{batt,p}}
\end{align*}
\]

The range of every variable was determined by conditions or experiences. Two scenarios of DG allowed operation time were considered, Scenario I: any hour every day, and Scenario II: between 9 am and 9 pm every day. Since some people live nearby this site, noise must be controlled. The objective was to minimize the LCOE of the RE system. The LPSP was set as the constraint for feasible solutions, and is represented by the \( \text{LPSP}_{\text{set}} \). The WTG types and sizes, PV panel tilt angles and sizes, battery capacities and DG sizes have a considerable influence on the power reliability and LCOE and can be optimized. For convenience, in every solution only one type of WTGs was applied. All the decision variables were integer. The optimization is a nonlinear integer programming problem with the constraint calculated by simulation.

From a practical point of view, the amount of radiation received using PV panels with a fixed tilt angle

### Table 1 | Items considered in LCOE analysis

<table>
<thead>
<tr>
<th>WTG</th>
<th>PV panel</th>
<th>DG</th>
<th>Wind inverter</th>
<th>Solar inverter</th>
<th>Bidirectional converter</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_p )</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>( M_p )</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>( F_p )</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Downloaded from https://iwaponline.com/jwrd/article-pdf/9/4/405/628993/jwrd0090405.pdf by guest
equal to the latitude is only slightly less than that using a monthly adjusted tilt angle. The fixed tilt angle method was employed because it would require less-expensive equipment and less maintenance (Hartley et al. 1999). The fixed tilt angle that would produce the most energy over the course of a year depends on the meteorological and topographical conditions of the location. In this optimization study, the fixed tilt angle was set as an integer in degrees with a possible range of tilt angles from $[0^\circ, 90^\circ]$.

The genetic algorithm

A genetic algorithm (GA) is a stochastic global search method based on natural selection, the process that drives biological evolution, and it does not require derivative or other auxiliary information. GAs can be used to solve both constrained and unconstrained optimization problems. Rudolph (Deb 2001) has proven that with an elitism strategy GAs can converge to the global optimal solution. The theories about the GA were explained in Chipperfield et al. The REROD system simulation, economic computation and GA optimization codes were written in the software package MATLAB. The GA functions used were from the Complex Optimization and Decision-Making Laboratory, University of Sheffield.

The decision variables of an individual are sequenced in the following order: $[\text{Type}_{WTG} N_{WTG} \beta N_{PV,p} N_{batt,p} N_{DG}]$, representing the type of WTG, the number of WTGs, the tilt angle of the PV, the number of strings of PV in parallel, the number of battery strings in parallel, and the number of DGs. Each individual is run through a simulation of its performance over 8,760 hours of 1 year. The LPSP of every individual is calculated in the simulation, and inspected to see if $\text{LPSP} > \text{LPSP}_{\text{set}}$. The refusal strategy was used, and individuals not up to grade are given up and new individuals are created. For individuals that meet the LPSP requirement, their objective values are computed (LCOE). The operational parameters about the GA are the number of individuals $N_{\text{ind}}$, crossover rate $R_{\text{cro}}$, mutation rate $R_{\text{mut}}$, and the number of generations $N_{\text{iter}}$. The GA is terminated after a pre-defined number of generations.

DATA

The third-version typical meteorological year data sets (TMY3s) contain hourly solar radiation and meteorological data for a 1-year period (Wilcox & Marion 2008). The location of Winslow, Arizona at latitude 35.033$^\circ$N, longitude 110.717$^\circ$W and elevation 1,490 m was chosen, which is nearest to Leupp among the locations in TMY3s. Global horizontal radiation and wind speed, which are shown in Figure 5, and diffuse horizontal radiation, extraterrestrial horizontal radiation and temperature in the TMY3s were employed, with the ground reflectance $\rho_G = 0.2$. Wind speed is assumed to be at a height of 10 m (Huld et al. 2018) above the ground surface. Note that the radiation and wind speed are highest during the spring months.

![Global Horizontal Radiation and Wind Speed](figure5.png)

Figure 5 | The TMY3s global horizontal radiation (a) and wind speed (b) at Winslow, AZ.
which are normally dry and windy. The radiation drops off in the summer due to seasonal monsoon rains that bring cloud cover, and the wind speed is less vigorous.

The technical specifications and economic data for each of the RE system components are shown in Table 2, along with the discount rate and analysis period. Note that there are three types of WTGs, all from the same manufacturer. The purpose of this optimization was to choose components with good, yet typical performance specifications and costs, and see what the best configuration is when faced with thousands of possible combinations of those components.

RESULTS AND DISCUSSION

The numbers of PV panels and batteries in series were determined as three and 24, respectively, in order to match the input voltage requirements of their respective inverters. As described above, the decision variables that define each individual in the GA’s population are organized in the following order: \([\text{Type}_{\text{WTG}} \ N_{\text{WTG}} \ \beta \ N_{\text{PV},p} \ N_{\text{batt},p} \ N_{\text{DG}}]\), where \(\beta\) is allowed to be an integer value in the range \([0^\circ, 90^\circ]\). The simulation results for each individual include the annual fuel consumption, DG running time, and battery bank Ah throughput. These outputs were used in the LCOE cost calculation, see Equation (14). For this research, the settings for the GA are \(N_{\text{ind}} = 500\), \(R_{\text{cro}} = 0.75\), \(R_{\text{mut}} = 0.7\), and \(N_{\text{gut}} = 1000\), and for the REROD simulation are \(LPS_{\text{set}} = 0\), \(SOC_{\text{start}} = 0.5\), and \(n = 10\) years. The lifetimes of the WTGs, wind inverters, solar inverters, bidirectional converters, and RO equipment employed in this study are 10 years, and that of DGs and batteries are shorter. Consequently, in terms of engineering realization, the best way to design the REROD system is using state-of-the-art technologies based on a 10-year life, acknowledging their will be value remaining in the PV panels and water tank at the end of the design life. In Table 2 some model constants and parameters used in the simulation are presented. In Table 3 the rest are presented.

Consider Scenario I, in which the DG can run in any hour every day. Running the GA resulted in individual \([2 \ 4 \ 31^\circ \ 7 \ 1 \ 1]\), having the lowest LCOE = 0.562 USD/kWh with LCOW = 3.835 USD/m³, and therefore being identified as the optimal solution. Figure 6 shows that the GA selected the optimal tilt angle \(\beta = 31^\circ\) that leads to the lowest LCOE for this configuration. Also, observe in Figure 6, that the LCOE changes very little for tilt angles close to 31°. Another interesting observation from Figure 6 is that there are big jumps in LCOE as the PV tilt angle changes. These step changes occur because as the tilt angle changes and the energy produced by the PV decreases, in order to supply adequate power during each hour of the year, additional replacements of DGs and/or batteries are required, causing increases in the costs. Figure 7 shows the DG daily running time for a TMY3 year. The minimum daily running time is 1 hour, and Figure 7 shows the DG runs longer in autumn and winter than in spring and summer. For the optimal solution, the annual DG running time is 2,938 hours (34% of the year), with a diesel consumption of 7,967 liters. Note, as described previously, when the DG was started, it was set to run at 75% of its rated power, 5.63 kW. After powering the RO load at 3.95 kW, the remaining 1.68 kW could be utilized to charge the battery bank. The charging current was about 34.3 A after rectifiers, which is 0.17 C for a battery string. A charging current less than 0.2 C is considered good (Xu & Kang 2013), and therefore 0.17 C charging current is proper. Figure 8 shows the monthly SOC of the battery bank for a TMY3 year, of the optimal solution. The average SOCs are high, which is in favor of battery lifetime. Table 4 chronologically shows the cost composition of the optimal solution in Scenario I. During the 10-year life of the power system, the battery bank was replaced 11 times and DG two times. Obviously, the battery bank experiences cyclic charge–discharge operation. Figure 9 shows monthly power generation of the optimal solution that June is the most diesel-saving month.

The LCOE of 0.562 USD/kWh for the optimal solution in Scenario I is more than four times the average residential electricity price in Arizona in 2018 of 0.13 USD/kWh (EIA n. d.). The LCOW of 3.835 USD/m³ was more than two times the average water price in Arizona in 2017 of 1.62 USD/m³ (Craig 2017). However, the LCOW is less than half of the 7.9 USD/m³ currently paid by residents that live in the area, and on the lower end of the range of 3 to 10 USD per 0.38 m³ paid for transported water by residents in the area (Haws 2014).

Consider Scenario II, in which the DG can run between 9 am and 9 pm every day. Running the GA resulted in
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate ($r$)</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Analysis period ($n$)</td>
<td>10 years</td>
<td></td>
</tr>
<tr>
<td>WTG (Tumo-int)</td>
<td></td>
<td>Tumo Int (2019)</td>
</tr>
<tr>
<td>Type ($Type_{WTG}$) and capital cost</td>
<td>Type I (1 kW 3-blade), 2,000 USD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type II (2 kW 3-blade), 4,000 USD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type III (3 kW 5-blade), 5,000 USD</td>
<td></td>
</tr>
<tr>
<td>Hub height ($H_2$)</td>
<td>30 m</td>
<td></td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>5% of capital cost</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 years</td>
<td></td>
</tr>
<tr>
<td>Wind inverter (SMA Windy Boy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency ($\eta_{inv,wind}$)</td>
<td>93%</td>
<td>Windy Boy 5000 (2019)</td>
</tr>
<tr>
<td>Capital cost</td>
<td>1 USD/W</td>
<td>Windy Boy 5000 (2019)</td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>3% of capital cost</td>
<td>Windy Boy 5000 (2019)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 years</td>
<td>SMA Windy Boy 5000 (2019)</td>
</tr>
<tr>
<td>PV panel (SolarWorld SW270 Black Mono)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum power</td>
<td>270 W</td>
<td>SolarWorld (2019)</td>
</tr>
<tr>
<td>Maximum power point current at ROCs ($I_{MP,ref}$)</td>
<td>8.81 A</td>
<td></td>
</tr>
<tr>
<td>Short circuit current at ROCs</td>
<td>9.44 A</td>
<td></td>
</tr>
<tr>
<td>Maximum power point voltage at ROCs ($V_{MP,ref}$)</td>
<td>30.9 V</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient for short circuit current ($\mu_{I,SC}$)</td>
<td>0.0004 A/°C</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient for open circuit voltage ($\mu_{V,OC}$)</td>
<td>−0.0031 V/°C</td>
<td></td>
</tr>
<tr>
<td>Module efficiency</td>
<td>16.10%</td>
<td></td>
</tr>
<tr>
<td>Capital cost</td>
<td>290 USD/piece</td>
<td></td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>3% of capital cost</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Solar inverter (SMA Sunny Boy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module efficiency ($\eta_{inv,solar}$)</td>
<td>95%</td>
<td>Solar Inverters (2019)</td>
</tr>
<tr>
<td>Capital cost</td>
<td>0.37 USD/W</td>
<td>SMA Sunny Boy (2019)</td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>3% of capital cost</td>
<td>SMA Sunny Boy (2019)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 years</td>
<td>SMA Sunny Boy (2019)</td>
</tr>
<tr>
<td>DG (Cummins SD 7.5 kW/60 Hz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated power</td>
<td>7.5 kW</td>
<td>Commercial Mobile (2019)</td>
</tr>
<tr>
<td>Maximum working power</td>
<td>5.63 (7.5*75%) kW</td>
<td>Amazon.com (2019)</td>
</tr>
<tr>
<td>Capital cost</td>
<td>9,472 USD</td>
<td>Filters for Perkins (2019)</td>
</tr>
<tr>
<td>Filters, duration time</td>
<td>500 h</td>
<td>Filters for Perkins (2019)</td>
</tr>
<tr>
<td>Filters, cost</td>
<td>50 USD</td>
<td>Emergency Power (2019)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10,000 h</td>
<td>Gasoline &amp; Diesel Fuel Update (2019)</td>
</tr>
<tr>
<td>Cost of diesel</td>
<td>0.86 USD/L</td>
<td></td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>5% of capital cost</td>
<td>HOMER (2019)</td>
</tr>
</tbody>
</table>

(continued)
individual [2 6 40° 20 24 0], which means diesel power was not chosen, having the lowest LCOE = 0.690 USD/kWh with LCOW = 4.476 USD/m³, and therefore being identified as the best solution. Figure 10 shows that for this hybrid wind/PV configuration all tilt angles in [40°, 50°] bring feasible solutions with equal LCOE values, and they deviate from the latitude 35°. Figure 11 shows the monthly SOC of the battery bank for a TMY3 year of the optimal solution. The average SOCs are high, which is in favor of battery lifetime. Figure 12 shows that solar PV largely provides power compared to wind. Table 5 chronologically shows the cost composition of the optimal solution in

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRLA battery (Enersys PowerSafe OpzV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated capacity</td>
<td>200 Ah, 2 V</td>
<td>PowerSafe OPzV Batteries</td>
</tr>
<tr>
<td>Mean lifetime energy throughput (mean Q_{\text{lifetime}})</td>
<td>117,500 Ah</td>
<td></td>
</tr>
<tr>
<td>Charging efficiency (\eta_{\text{batt}})</td>
<td>0.85</td>
<td>HOMER (2019)</td>
</tr>
<tr>
<td>Discharging efficiency (\eta_{\text{disch,batt}})</td>
<td>1</td>
<td>HOMER (2019)</td>
</tr>
<tr>
<td>Capital cost</td>
<td>300 USD/kWh</td>
<td>PowerSafe OPzV Batteries</td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>3% of capital cost</td>
<td>PowerSafe OPzV Batteries</td>
</tr>
<tr>
<td>Lifetime</td>
<td>(shown in Figure 2)</td>
<td>O’Connor (2016)</td>
</tr>
<tr>
<td>Bi-directional converter (SMA Sunny Island)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectifier efficiency (\eta_{\text{rect,b}})</td>
<td>94.50%</td>
<td>SUNNY ISLAND 4548 (2019)</td>
</tr>
<tr>
<td>Inverter efficiency (\eta_{\text{inv,b}})</td>
<td>98%</td>
<td>SUNNY ISLAND 4548 (2019)</td>
</tr>
<tr>
<td>Capital cost</td>
<td>0.7 USD/W</td>
<td>SMA Sunny Island (2019)</td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>3% of capital cost</td>
<td>SMA Sunny Island (2019)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 years</td>
<td>SMA Sunny Island (2019)</td>
</tr>
<tr>
<td>RO equipment (Water business: DS-2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated capacity</td>
<td>18–23 m³/d</td>
<td>Water Business (2019)</td>
</tr>
<tr>
<td>Capital cost</td>
<td>26,850 USD</td>
<td>Water Business (2019)</td>
</tr>
<tr>
<td>Maintenance cost of RO system</td>
<td>0.2 USD/m³</td>
<td>Maleki (2018)</td>
</tr>
<tr>
<td>Membrane replacement cost</td>
<td>0.06 USD/m²</td>
<td>Maleki (2018)</td>
</tr>
<tr>
<td>Number of membrane replacements per year</td>
<td>2</td>
<td>Maleki (2018)</td>
</tr>
<tr>
<td>Cost of chemicals</td>
<td>0.06 USD/m²</td>
<td>Maleki (2018)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 years</td>
<td>Water Business (2019)</td>
</tr>
<tr>
<td>Water tank</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital cost</td>
<td>255 USD/m³</td>
<td>(Maleki 2018)</td>
</tr>
<tr>
<td>Annual maintenance cost</td>
<td>3% of capital cost</td>
<td></td>
</tr>
</tbody>
</table>

ROC, reference operating condition.

<table>
<thead>
<tr>
<th>Model constant</th>
<th>G_{\text{ref}}</th>
<th>T_{\text{C,ref}}</th>
<th>\alpha</th>
<th>\rho_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>1,000 W/m²</td>
<td>25 °C</td>
<td>1/7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>n</th>
<th>N_{\text{batt,s}}</th>
<th>N_{\text{ind}}</th>
<th>N_{\text{PV,s}}</th>
<th>P_{\text{DEM}}</th>
<th>R_{\text{batt,f}}</th>
<th>R_{\text{cro}}</th>
<th>R_{\text{mut}}</th>
<th>DOD</th>
<th>LPSP_{\text{set}}</th>
<th>SOC_{\text{start}}</th>
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</thead>
<tbody>
<tr>
<td>Values</td>
<td>10 years</td>
<td>24</td>
<td>500</td>
<td>1,000</td>
<td>3</td>
<td>3.95 kW</td>
<td>20 years</td>
<td>0.75</td>
<td>0.7</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>
Scenario II. During the 10-year life of the system, the battery bank was not changed.

The LCOE of 0.690 USD/kWh for the best solution is more than five times the average residential electricity price 0.13 USD/kWh. The LCOW of 4.476 USD/m³ is more than half of the 7.9 USD/m³ currently paid by residents there, and near the lower end of the range of 3 to 10 USD per 0.38 m³ for transported water.

Figure 13 shows an index comparison of Scenario I and Scenario II. Wind/PV power system is a little more expensive than Wind/PV/DG power system. The battery bank capacity of solution [2 4 β 7 1 1] was much larger than that of solution [2 4 β 7 1 1]. Dispatchable DG can provide power at times when renewable energy is insufficient, so configurations with DGs need a small battery capacity and avoid lost energy due to the battery bank round-trip efficiency at 85%. On the contrary, configurations of pure renewable energy need dispatchable battery banks to complement the intermittent renewable energy, so the battery bank capacity is large.

Energy outputs of the three types of WTGs for a TMY3 year is shown in Figure 14. The type II (2 kW) WTG produces the maximum energy, which means the GA made the right choice. The optimal tilt angles of the optimal solution to Scenario I are less than the latitude, while that of the optimal solution to Scenario II are greater than the latitude. It is often true that a PV panel will produce the most energy over the course of a year if tilted at an angle equal to the latitude. Figure 15 shows an example. The important point here is that for a hybrid power system containing wind and solar energy, the optimal tilt angle is not necessarily equal to latitude, but rather is dependent upon the combination of energy sources and their timing. The optimal tilt angle for the hybrid system must be found in the context of the performance of the entire system and not any single component or parameter.

CONCLUSIONS

In this paper, two optimal configurations of a hybrid power system for reverse osmosis desalination were found, in
Table 4 | The cost composition of the optimal solution \([2 4 31 7 1]\) in Scenario I (the unit is USD).

<table>
<thead>
<tr>
<th>n (year)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>Investment</td>
<td>9,472</td>
<td>0</td>
<td>0</td>
<td>9,472</td>
<td>0</td>
<td>0</td>
<td>9,472</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>M&amp;O</td>
<td>724</td>
<td>724</td>
<td>724</td>
<td>724</td>
<td>724</td>
<td>724</td>
<td>724</td>
<td>724</td>
<td>724</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
<td>6,852</td>
</tr>
<tr>
<td>PV</td>
<td>Investment</td>
<td>8,222</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>M&amp;O</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
</tr>
<tr>
<td>Wind</td>
<td>Investment</td>
<td>24,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>M&amp;O</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
</tr>
<tr>
<td>Battery bank</td>
<td>Investment</td>
<td>2,880 \times 2</td>
<td>2,880</td>
<td>2,880</td>
<td>2,880</td>
<td>2,880</td>
<td>2,880</td>
<td>2,880 \times 2</td>
<td>2,880</td>
<td>2,880</td>
</tr>
<tr>
<td></td>
<td>M&amp;O</td>
<td>86</td>
<td>86</td>
<td>86</td>
<td>86</td>
<td>86</td>
<td>86</td>
<td>86</td>
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<tr>
<td>Bidirectional converter</td>
<td>Investment</td>
<td>1,344</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td>M&amp;O</td>
<td>40</td>
<td>40</td>
<td>40</td>
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</tr>
</tbody>
</table>

Figure 9 | Monthly power generation of the optimal solution \([2 4 31 7 1]\) in Scenario I.

Figure 10 | LCOE versus PV panel tilt angle for solution \([2 6 20 24 0]\) in Scenario II.

Figure 11 | Monthly SOC of the battery bank of the optimal solution \([2 6 40 20 24 0]\) in Scenario II.

Figure 12 | Monthly power generation of the optimal solution \([2 6 40 20 24 0]\) in Scenario II.
terms of two scenarios according to DG allowed running time, respectively. When the DG can run any hour every day, the optimal configuration was a PV/wind/DG/battery combination with LCOW = 3.84 USD/m³. When the DG can run between 9 am and 9 pm every day, the optimal configuration was a PV/wind/battery combination with LCOW = 4.48 USD/m³. Both the LCOWs were about half of the 7.9 USD/m³ currently paid by residents that live in the area. For a hybrid power system with PV, the optimal tilt angle of fixed PV panels was not necessarily equal to the latitude, and the LCOE was fairly insensitive to photovoltaic panel tilt angle over a range. As demonstrated in this work, the WTG type can be defined as a decision variable, with the GA selecting the most appropriate type of generator. Configurations with DGs needed a small battery capacity to avoid lost energy due to the battery bank efficiency, while configurations of pure renewable energy needed a large

| Table 5 | The cost composition of the optimal solution [2 6 40 20 24 0] in Scenario II (the unit is USD). |
|----------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
|          | (year) 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| PV       | Investment | 23,490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|          | M&O | 705 | 705 | 705 | 705 | 705 | 705 | 705 | 705 |
| Wind     | Investment | 36,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|          | M&O | 1,800 | 1,800 | 1,800 | 1,800 | 1,800 | 1,800 | 1,800 | 1,800 | 1,800 |
| Battery bank | Investment | 69,120 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|          | M&O | 2,074 | 2,074 | 2,074 | 2,074 | 2,074 | 2,074 | 2,074 | 2,074 | 2,074 |
| Bidirectional converter | Investment | 32,256 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|          | M&O | 968 | 968 | 968 | 968 | 968 | 968 | 968 | 968 | 968 |
battery bank capacity since dispatchable battery banks can complement the intermittent renewable energy.

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