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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 m³, which can minimize 60,096.9 m³ of outsourced freshwater with a reasonable total annual cost of 503,159 \$/year.

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1. Introduction

World energy demand is expected to increase to several times its current level over the next 50 years (Darton, 2003). RES¹ 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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¹ Renewable energies sources.

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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

δ	Conversion efficiency
σ	Transfer efficiency
α	Self-discharge efficiency
γ	Specific RO power consumption

Remote communities are often located in areas with access to sea-water or brackish groundwater. Therefore, for such communities, RO² 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 CO₂ 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 pro-

cesses (Wu et al., 2015). A BS³ 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 PV⁴ 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).

PA⁵ 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 PoPA⁶ has been used by many researchers who performed numerical tools of PoPA including a PoCT⁷ and SCT⁸ 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 EPoPA⁹ 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

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.

² Reverse osmosis.

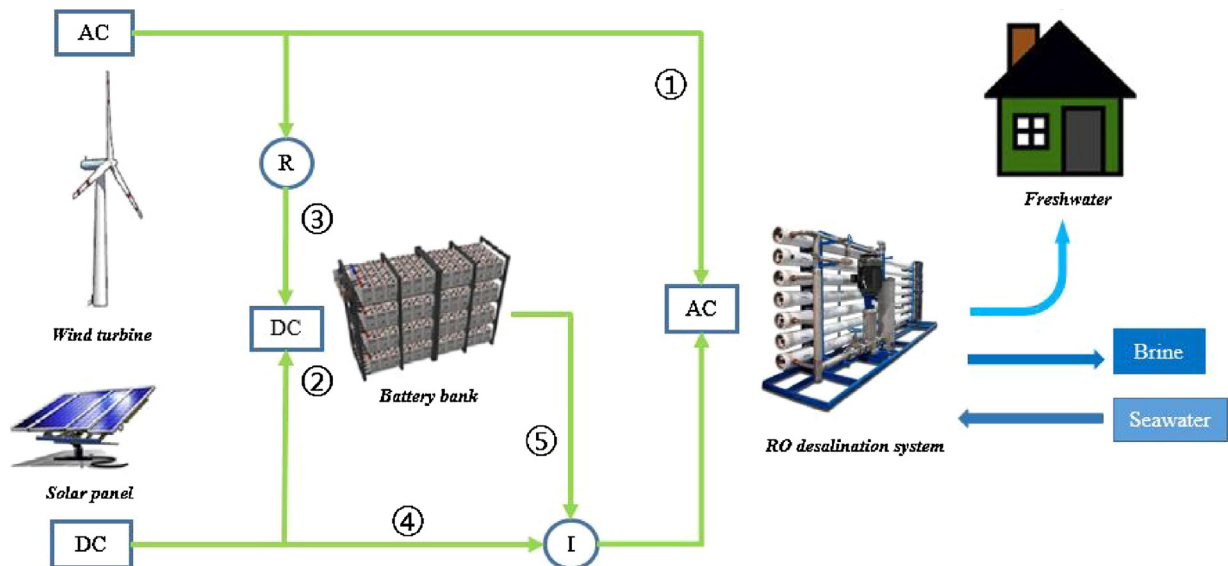


Fig. 1 – Hybrid power system with a battery and RO desalination system (Janghorban Esfahani et al., 2015).

Table 1 – Scenario strategies and the number of PV panel and wind turbine.

Scenario	Description	Number of PV panel	Number of wind turbine
Scenario 1	90% of power demand required from PV panel; 10% of power demand required from wind turbine	419	15
Scenario 2	10% of power demand required from PV panel; 90% of power demand required from wind turbine	47	135
Scenario 3	50% of power demand required from PV panel; 50% of power demand required from wind turbine	233	75

efficiency of 90% and a self-discharge battery rate of 0.004%/h (Rozali et al., 2013). A case study in London is carried out for a whole year operation with RES-BS-RO system to produce freshwater and satisfy the water demand.

2. Methodology

2.1. System configuration

As shown in Fig. 1, the PV arrays and wind turbines generate electricity and deliver to the RO desalination system to produce freshwater, whilst the battery is used to store the extra electricity and export power to the RO system when is necessary. The RO desalination system can only directly use AC¹⁰ electricity provided by the wind turbine, and the battery bank can only store DC¹¹ electricity provided by the solar panels. The AC electricity generated by wind turbine can be delivered directly to the RO system without electricity losses through route 1 to produce freshwater. The DC electricity generated by solar panels can be stored in the battery without electricity losses through route 2. The excess AC electricity generated by the wind turbine can be converted into DC electricity by a rectifier and can be stored in the battery bank through route 3; in this conversion, some AC electricity is lost. The losses occur due to charging and discharging of the battery when exits excess DC electricity and during net electricity conversion to DC. When the electricity generated by wind turbines is

not sufficient for delivery to the RO system, electricity can be provided through routes 4 and 5. The DC electricity generated by solar panels is converted to AC electricity through route 4, where a portion of power is lost due to conversion of DC to AC by the inverter. Through route 5, the stored electricity in the battery is converted to AC electricity by the inverter and then is delivered to the RO system. Therefore, a portion of power is lost within the inverter.

In order to reduce the power losses in the system, the following energy management strategies are described (Rozali et al., 2013):

- 1) The AC electricity generated by the wind turbine is directly delivered to the RO system.
- 2) The excess AC electricity is converted to DC electricity and stored in the battery.
- 3) If the electricity generated by AC electricity is not suitable for RO system, then, the DC electricity generated by the PV array can be converted into AC electricity to deliver to the RO system.
- 4) If the electricity generated by PV array is greater than the required RO electricity, then, the excess DC electricity is stored in the battery.
- 5) If the AC electricity generated by the wind turbine and DC electricity generated by the PV array is not adequate for the RO system, then, the DC electricity is discharged from the battery and converted to AC electricity.
- 6) If the electricity generated by wind turbine and PV panel are not adequate for the RO system, an outsourced electricity is purchased from the grid.

¹⁰ Alternating current.

¹¹ Direct current.

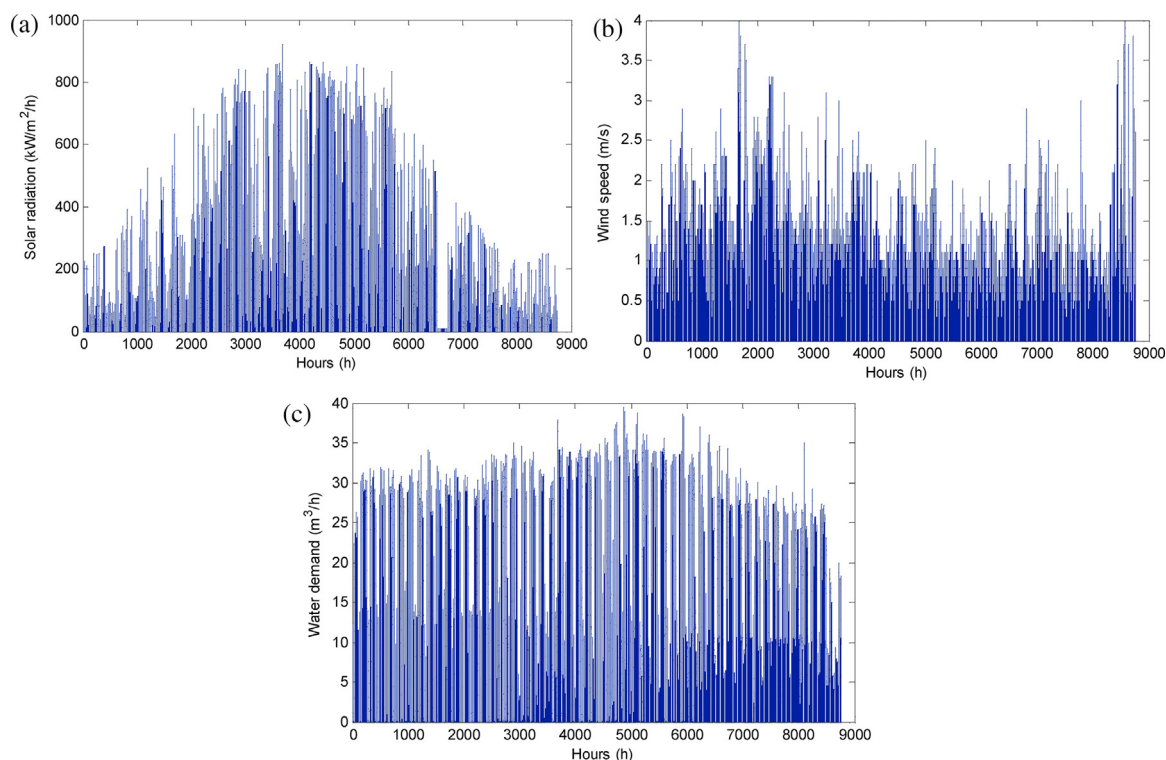


Fig. 2 – The hourly data of (a) solar radiation, (b) wind speed, and (c) water demand in London, UK.

Three different scenarios are introduced based on the energy management strategy to develop three possible yearly case study shown in Table 1. The electricity requirement by the RO desalination system comes from AC form electricity (wind turbine) and DC form electricity (PV panel). For the first scenario, 10% of energy required by RO comes from the wind turbine and 90% from PV panel. For the second scenario, wind turbine is used to fulfill 90% of the RO power demand and the 10% from PV panel. For the third scenario, it is assumed to have the same share of PV panel (50%) and wind turbine (50%).

2.2. Data extraction

In this study, the solar radiation and wind speed data were extracted from the London air quality network home page, and dynamic freshwater demand data were extracted from home office data for energy and water consumption during the year 2013 as a case study in London—UK. The hourly data of solar radiation, wind speed, and water demand represents one year operation and are shown in Fig. 2. A case study in London—UK is carried out for one year operation. PoPA technique is applied using hourly data during the whole year. For 24 h operation, the cascade table is used to explain the algorithm.

2.3. Determination of the number of PV panel and wind turbine

The number of PV panel and wind turbine are determined for each scenario based on the scenario strategies for each month, dividing the average monthly power demand by the unit power generated by RES. The overall quantity of PV panel and wind turbine is the maximum number among twelve months which are summarized in Table 1 for all three scenarios.

2.4. Power pinch analysis

The PoCT¹² was implemented in this study to determine the MOES¹³ and the AEEND¹⁴ of each normal operation day. The SCT was applied in order to determine the WE,¹⁵ NE,¹⁶ BC,¹⁷ and OFW.¹⁸

2.4.1. Power cascade table

All the equations of the electricity generated by PV panels, wind turbines and the electricity required by the RO system for the case study is given in Appendix A.

The PoCT is shown in Table 2 and the steps for the construction for daily operation are as follows:

Step 1. Determination of time interval

The first column of Table 2 shows the time interval from '1' to '24' h, and the second column shows the time duration between two time intervals, which is one hour.

Step 2. Calculation of DC source, AC source, and AC demand

Columns 3–5 show the DC source, AC source, and AC electricity demand of the RO system during each time interval, which are calculated by Eqs. (A.1)–(A.3), respectively.

Step 3. Summation of electricity generated by AC electricity

Column 6 shows the summation of the conversion of DC electricity to AC and the electricity generated by AC, considering losses through the inverter calculated by Eq. (A.4).

Step 4. Calculation of net AC electricity surplus and deficit

Column 7 shows the NetAC,¹⁹ which is the difference between generated AC electricity and AC electricity demand

¹² Power cascade table.

¹³ Minimum outsourced electricity supply.

¹⁴ Available excess electricity for the next day.

¹⁵ Waste electricity.

¹⁶ Needed electricity.

¹⁷ Battery capacity.

¹⁸ Outsourced freshwater.

¹⁹ Net electricity of AC surplus and AC deficit.

Table 2 – Power cascade table for the first operation day.

1 Time (h)	2 Time interval (h)	3 DC source (GP_{DC}) (kWh)	4 AC source (GP_{AC}) (kWh)	5 AC demand (DP_{RO}) (kWh)	6 Σ Electricity sources (kWh)	7 Net electricity sur/def ($NetAC$) (kWh)	8 Infeasible electricity (IE) (kWh)	9 Feasible electricity cascade (kWh)
1	1	0.00	7.72	0.00	7.72	7.72	0	584.09
2	1	0.00	3.63	0.00	3.63	3.63	11.35	591.81
3	1	0.00	1.32	33.36	1.32	−32.04	−20.69	595.44
4	1	0.00	2.29	3.75	2.29	−1.46	−22.16	563.40
5	1	0.00	2.29	0.00	2.29	2.29	−19.87	561.94
6	1	0.67	2.29	0.00	2.92	2.92	−16.95	564.22
7	1	7.99	1.32	0.03	8.92	8.89	−8.06	567.14
8	1	16.90	2.29	0.00	18.34	18.34	10.28	576.03
9	1	22.73	2.29	68.88	23.88	−45.00	−34.72	594.37
10	1	24.06	7.72	30.78	30.58	−0.20	−34.92	549.37
11	1	15.99	10.58	75.00	25.77	−49.23	−84.15	549.17
12	1	15.99	7.72	75.00	22.90	−52.10	−136.25	499.94
13	1	15.24	7.72	75.00	22.19	−52.81	−189.06	447.84
14	1	2.83	14.09	75.00	16.78	−58.22	−247.28	395.03
15	1	0.58	5.42	75.00	5.97	−69.03	−316.31	336.81
16	1	0.00	2.29	75.00	2.29	−72.71	−389.02	267.78
17	1	0.00	0.68	75.00	0.68	−74.32	−463.35	195.07
18	1	0.00	0.68	47.31	0.68	−46.63	−509.98	120.75
19	1	0.00	0.68	45.09	0.68	−44.41	−554.39	74.11
20	1	0.00	3.63	33.33	3.63	−29.70	−584.09	29.70
21	1	0.00	10.58	0.06	10.58	10.52	−573.57	0.00
22	1	0.00	10.58	0.03	10.58	10.55	−563.01	10.52
23	1	0.00	29.04	0.00	29.04	29.04	−533.97	21.08
24	1	0.00	35.72	0.03	35.72	35.69	−498.29	50.12
								85.81

of the RO system at each time interval and is calculated by Eq. (A.5).

Step 5. Determination of pinch point, MOES, and AEEND

Considering the RES–BS–RO system as an off-grid system, the electricity is not delivered to the RO system at the start point of operation. Column 8 shows the infeasible electricity (IE) at each time interval, which is calculated based on column 7 using Eq. (A.6).

Table 2 shows that the pinch point is located at 20 h, where the MOES is 584.09 kWh and the AEEND is 85.81 kWh, and are listed in the first and last cells of column 9, respectively. For a normal operation day AEEND, can be used for the next day, however, this amount cannot achieve the demand of one day's electricity consumption (584.09 kWh). Consequently, an extra 498.28 kWh of electricity is required from another source to satisfy the load demand. The feasible electricity described in column 9 is calculated by Eq. (A.6) based on the cascade technique of column 7.

2.4.2. Storage cascade table

All the equations for the construction of SCT are shown in Table 3. Electricity sources in the forms of DC source (GP_{DC}), AC source (GP_{AC}) and AC demand (DP_{RO}), are calculated using solar radiation, wind speed, and water demand and are listed in columns 1–3 of Table 4, respectively.

It is assumed that the RO system first uses the available AC electricity and then uses DC electricity directly from the PV array or indirectly from the battery. Column 4 describes the DC electricity required for the RO system at each time interval, which is calculated by Eq. (1) of Table 3.

Column 5 presents the DC electricity required from the battery considering losses in the conversion from DC to AC electricity, which is calculated by Eq. (2).

Columns 4 and 5 show the positive values of the DC electricity required by the RO system and from the battery, respectively, at each time interval, as calculated by Eqs. (1) and (2). The amounts of electricity stored in the battery as surplus of AC and DC are listed in columns 6 and 7, respectively. Column 6 shows the positive values of AC surplus that first has to be converted to DC electricity to store in the battery, and column 7 shows the positive values of DC surplus that can be directly stored in the battery. When the AC electricity generated by the wind turbine and DC electricity generated by solar panels exceed the demand of the AC and DC load, the electricity is directly transferred from the energy sources to the loads through routes 1 and 4.

To calculate the WE, NE, BC, and OFW refers to columns 8 and 9 which show the charging (CH) and discharging (DCH) of the battery in each time interval, and are calculated by Eqs. (3) and (4), respectively where CH and DCH shown in Appendix B are the charging and discharging of the battery (kWh), respectively, and σ is the charging & discharging efficiency, which is 90% (Mahmoudi et al., 2008).

Infeasible storage capacity (ISC) and infeasible outsourced electricity (IOE) both in (kWh) are described in columns 10 and 11, respectively, and are calculated by Eqs. (5) and (6) taking into account the battery self-discharge rate (α), charge and discharge efficiency (σ). In order to transfer energy from one hour to another, the energy in battery will be stored for a certain period (one hour) before it be used (Ho et al., 2016). Therefore once the energy stored in the battery the self-discharge of battery need to be considered, and the amount of energy transfer to the next time interval should deduct the self-discharge energy, which is 0.004%/h (Mahmoudi et al., 2008).

Based on Eqs. (5) and (6), when the battery bank is completely discharged, the RO system requires outsourced electricity to generate freshwater.

Table 3 – Equations used for the construction of SCT.

Description	Equation
Electricity surplus & deficit for AC and DC	$DCElectricityrequiredfromtheROsystem = DP_{RO} - GP_{AC}$ (1)
DC electricity required from the battery	$DCElectricityrequiredfromthebattery = DP_{RO} - GP_{AC} - GP_{DC} \times \delta$ (2)
CH and DCH of the battery	$CH = GP_{AC} \times \sigma + GP_{DC}$ (3)
	$DCH = electricityneededfrombattery/\sigma$ (4)
Infeasible storage capacity	$ISC_{i+1} = ISC_i \times (1 - \alpha) + CH_{i+1} \times \sigma - DCH_{i+1}/\sigma$ (5)
	$IOE_i = -ISC_i / (\sigma \times \delta)$ (6)
Feasible storage capacity	$AEEND = ISC_{24}$ (7)
	$MOES = \sum_{i=1}^{24} IOE_i / (1 - \alpha)^i$ (8)
AEEND and MOES assumption	If $AEEND_{j-1} \geq MOES_j$, $SC_{0,j} = MOES_j$ else $SC_{0,j} = AEEND_j$ (9)
Minimum outsourced freshwater	$FW_{RO} = (DP_{RO} - FOE)/\gamma$ (10)
	$OFW = FWD - FW_{RO}$ (11)

At the 24 h time interval, the electricity stored in the battery, can be used for the next day representing the AEEND. This AEEND is used the next day to satisfy the minimum outsourced electricity surplus, which is represented by MOES. MOES and AEEND can be calculated through Eqs. (7) and (8), respectively where ISC_{24} is the infeasible storage capacity at 24 h (kWh).

For a normal operation day, if the amount of AEEND at 24 h is greater or equal than MOES, then the electricity stored in the battery on the previous day ($j - 1$) (where j represents the day) can meet the needed electricity demand of the next day. If the amount of AEEND at 24 h is less than MOES, the electricity stored in the battery in the previous day cannot meet the needed electricity demand of the next day. This assumption is represented by Eq. (9). See Table 3, where $SC_{0,j}$ represents the amount of electricity that can be used at “0” h (kWh) during a normal operation day.

Based on the amount of $SC_{0,j}$, a cascaded technique was applied with the amounts of CH (column 8) and DCH (column 9) of the battery to obtain the feasible storage capacity (FSC) at each time interval using Eq. (5), which is listed in column 12, and the OE, which is listed in column 13 and calculated with Eq. (6). The value of “0” which is listed in column 12, means that the battery is discharged at that time interval, in that case, the RO system needs outsourced electricity to generate fresh water and can be used to satisfy the water demand.

Based on the SCT, AEEND can be stored in the battery and is available for use the next day, therefore, WE and NE can be defined during a normal operation day as follows.

According to the assumption above, if “ $AEEND_{j-1} \geq MOES_j$,” consequently NE is zero, and WE is the difference between $AEEND_{j-1}$ and $MOES_j$. If “ $AEEND_{j-1} < MOES_j$,” consequently NE is the difference between $MOES_j$ and $AEEND_{j-1}$, and WE is zero. As presented in Table 4, the AEEND at 24 h is 73.36 kWh, and the MOES is 531.57 kWh. For this case, MOES is greater than AEEND, therefore, an amount of 458.21 kWh represents the NE. The maximum battery capacity for this study is 83.05 kWh for one operation day, which is listed in column 12. This size of the battery depends on the battery’s charge and discharge requirements and the efficiency of the charger and the other system components.

The fresh water produced by the RO system is calculated based on the power delivered to the RO system (DP_{RO}) and the feasible outsourced electricity (FOE) which is determined by Eq. (10), and is listed in column 14 where FW_{RO} is the production freshwater by the RO system (m^3) and OFW is the dynamic

hourly freshwater demand (m^3) (FWD), which is listed in column 15. The OFW is described in column 16 using Eq. (11).

The total freshwater produced by the RO system (FW_{RO}) is $85.47 m^3$, and the minimum outsourced freshwater is $191.23 m^3$ on a normal operation day. The total freshwater produced by the RO system is less than the minimum outsourced freshwater. This deficiency of freshwater during a normal day indicates a lack of water for use on the next day, which suggests a need to increase the RO system size.

3. Optimization algorithm of the RES-BS-RO system

Fig. 3 shows the algorithm divided into three parts. Part one, the algorithm was designed for 1 year operation from the SCT steps to determine the MOES and AEEND using Eqs. (7) and (8), respectively. Part two, AEEND was calculated for each day of operation according to the assumption described in Section 2.4.2. Part three, the feasible storage cascade was calculated for one day of operation, using the cascading technique, taking into account the amount of electricity delivered from the previous day, to calculate the maximum battery capacity in one year of operation based on the description in Section 2.5. The minimum outsourced freshwater was calculated considering 365 days, based on Eq. (17), taking into account the produced fresh water by the RO system and the dynamic hourly water demand.

3.1. Analysis of the RES-BS-RO system

Fig. 4 shows daily data of the NE and WE respectively, during one year of operation. For the first scenario, the WE and NE in Fig. 4a shows the maximum WE exited in March with 5184 kWh of wasted electricity. The maximum average monthly WE appeared in March with 660.22 kWh/day and the minimum average monthly WE occurred in November with 4 kWh/day. The NE follow the same tendency as the water demand, showing high amounts during the last six months of year and low amounts during the first six months of the year. The average NE for the whole year is 427.04 kWh/day. The WE and NE for scenarios two and three are shown in Fig. 4b and c, respectively. In these two scenarios, the WE are much higher than the NE in terms of the average value during the year operation. Comparing the two scenarios the WE have the highest value of the same day in March with 51,839 kWh and 28,511 kWh, respectively. Compared with scenario one, a high fraction of energy demand from wind power result in high

Table 4 – Storage cascade table for the first operation day .

Time (h)	Interval (h)	1 DC source GP _{DC} (kWh)	2 AC source GP _{AC} (kWh)	3 AC demand DP _{RO} (kWh)	4 DP _{RO} need from GP _{DC} (kWh)	5 DP _{RO} need from Battery (kWh)	6 AC surplus (kWh)	7 DC sur- plus (kWh)	8 Charging CH (kWh)	9 Discharging DCH (kWh)	10 Infeasible storage capacity ISC (kWh)	11 Infeasible outsource electricity IOE (kWh)	12 Feasible storage capacity FSC (kWh)	13 Feasible outsource electricity FOE (kWh)	14 Freshwater produce by RO (m ³)	15 Freshwater demand FWD (m ³)	16 Outsource Fresh Water OFW (m ³)
1	1	0.00	7.72	0.00	0.00	0.00	7.72	0.00	7.33	0.00	6.60	0.00	79.95	0.00	0.00	0.00	0.00
2	1	0.00	3.63	0.00	0.00	0.00	3.63	0.00	3.45	0.00	9.70	0.00	83.05	0.00	0.00	0.00	0.00
3	1	0.00	1.32	33.36	32.04	32.04	0.00	0.00	0.00	33.72	0.00	23.74	45.58	0.00	11.12	11.12	0.00
4	1	0.00	2.29	3.75	1.46	1.46	0.00	0.00	0.00	1.54	0.00	1.46	43.87	0.00	1.25	1.25	0.00
5	1	0.00	2.29	0.00	0.00	0.00	2.29	0.00	2.17	0.00	1.95	0.00	45.82	0.00	0.00	0.00	0.00
6	1	0.67	2.29	0.00	0.00	0.00	2.29	0.67	2.84	0.00	4.51	0.00	48.37	0.00	0.00	0.00	0.00
7	1	7.99	1.32	0.03	0.00	0.00	1.29	7.99	9.22	0.00	12.81	0.00	56.67	0.00	0.01	0.01	0.00
8	1	16.90	2.29	0.00	0.00	0.00	2.29	16.90	19.07	0.00	29.97	0.00	73.83	0.00	0.00	0.00	0.00
9	1	22.73	2.29	68.88	66.59	45.00	0.00	0.00	0.00	47.37	0.00	19.37	21.20	0.00	22.96	22.96	0.00
10	1	24.06	7.72	30.78	23.06	0.20	0.00	0.00	0.00	0.21	0.00	0.20	20.96	0.00	10.26	10.26	0.00
11	1	15.99	10.58	75.00	64.42	49.23	0.00	0.00	0.00	51.82	0.00	49.23	0.00	31.32	14.56	27.01	12.45
12	1	15.99	7.72	75.00	67.28	52.10	0.00	0.00	0.00	54.84	0.00	52.10	0.00	52.12	7.63	25.95	18.32
13	1	15.24	7.72	75.00	67.28	52.81	0.00	0.00	0.00	55.59	0.00	52.81	0.00	52.84	7.40	26.05	18.65
14	1	2.83	14.09	75.00	60.91	58.22	0.00	0.00	0.00	61.29	0.00	58.22	0.00	58.26	5.59	25.41	19.82
15	1	0.58	5.42	75.00	69.58	69.03	0.00	0.00	0.00	72.66	0.00	69.03	0.00	69.07	1.99	29.22	27.23
16	1	0.00	2.29	75.00	72.71	72.71	0.00	0.00	0.00	76.54	0.00	72.71	0.00	72.76	0.76	29.00	28.24
17	1	0.00	0.68	75.00	74.32	74.32	0.00	0.00	0.00	78.23	0.00	74.32	0.00	74.37	0.23	26.51	26.28
18	1	0.00	0.68	47.31	46.63	46.63	0.00	0.00	0.00	49.09	0.00	46.63	0.00	46.67	0.23	15.77	15.54
19	1	0.00	0.68	45.09	44.41	44.41	0.00	0.00	0.00	46.75	0.00	44.41	0.00	44.45	0.23	15.03	14.80
20	1	0.00	3.63	33.33	29.70	29.70	0.00	0.00	0.00	31.26	0.00	29.70	0.00	29.72	1.21	11.11	9.90
21	1	0.00	10.58	0.06	0.00	0.00	10.52	0.00	10.00	0.00	9.00	0.00	9.00	0.00	0.02	0.02	0.00
22	1	0.00	10.58	0.03	0.00	0.00	10.55	0.00	10.03	0.00	18.02	0.00	18.02	0.00	0.01	0.01	0.00
23	1	0.00	29.04	0.00	0.00	0.00	29.04	0.00	27.59	0.00	42.85	0.00	42.85	0.00	0.00	0.00	0.00
24	1	0.00	35.72	0.03	0.00	0.00	35.69	0.00	33.90	0.00	73.36	0.00	73.36	0.00	0.01	0.01	0.00

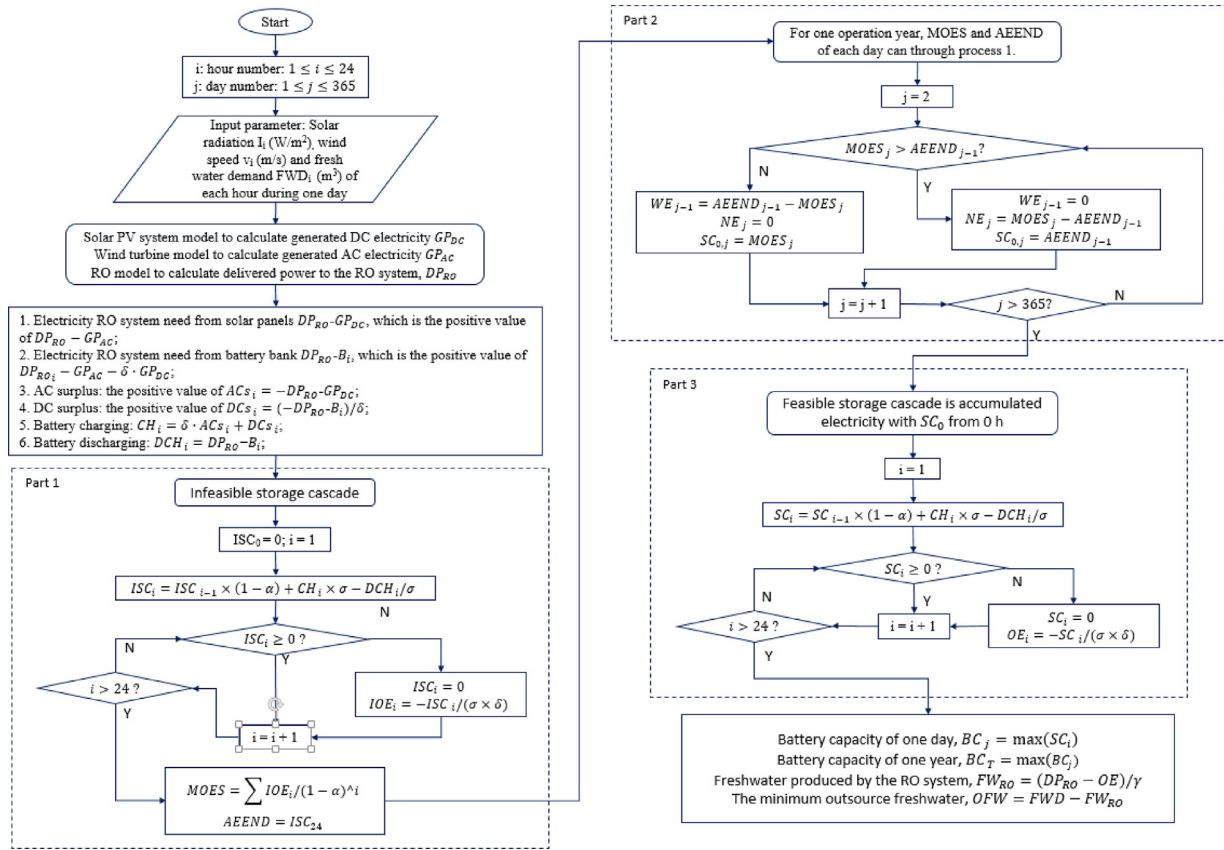


Fig. 3 – Optimization algorithm-based storage cascade analysis.

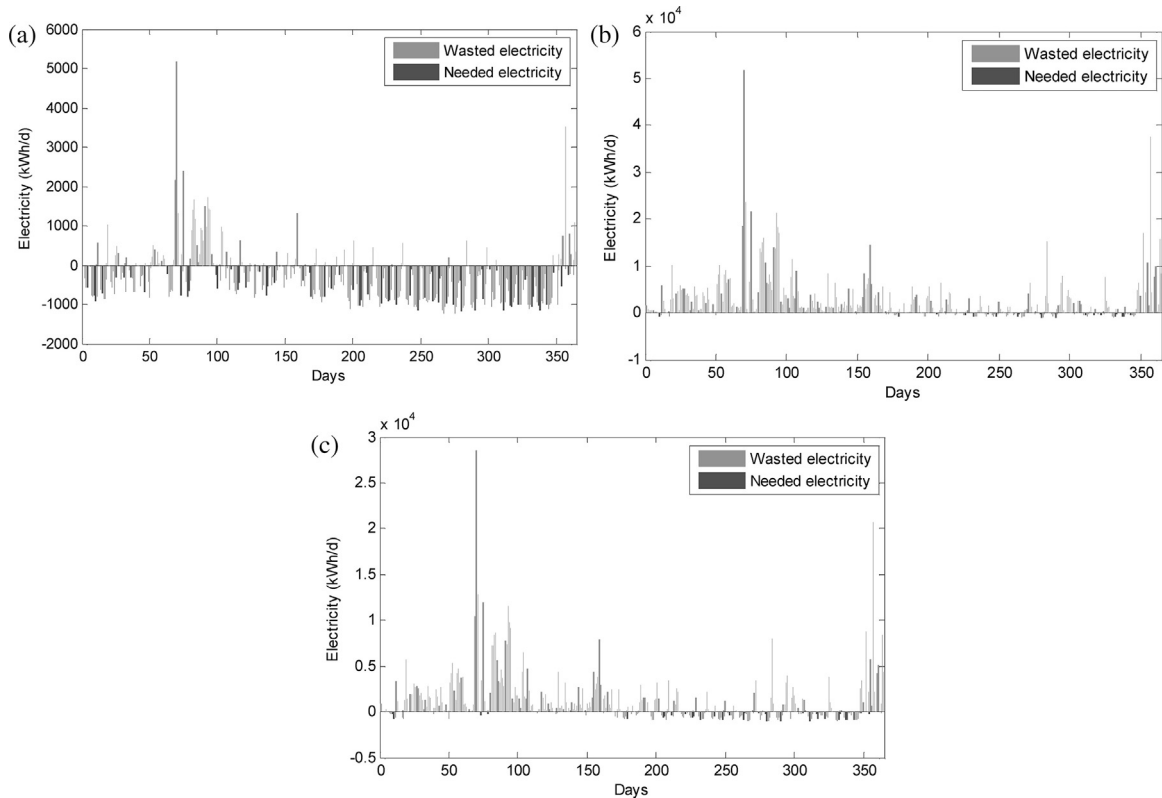


Fig. 4 – The daily wasted and needed electricity of three scenarios (a) scenario one, (b) scenario two, (c) scenario three.

electricity waste during the first semester of the year, in which the wind speed are higher in these month compared with the lower wind speed in the second semester (Fig. 2b).

Fig. 5 shows the battery capacities by each day during one year of operation, calculated using the algorithm. For scenario one, the maximum battery capacity is 936.29 kWh during December. The lead–acid battery life is significantly shortened when it is discharged very rapidly or during the frequent deep cycles. In order to have a better use of the battery, the DoD²⁰ of the battery bank is assumed to be 80% of its maximum capacity (Rozali et al., 2013). Therefore, in this study, the actual battery capacity is 1170.36 kWh during the year 2013. This energy stored in the battery can be used directly to power DC loads or it can be sent to the inverter to power AC loads. This amount of battery capacity is sufficient to provide electricity without running additional generators. For scenario two, the maximum battery capacity is 579.28 kWh appears on August month. And for scenario three, the maximum battery capacity is 784.63 kWh in October. The battery capacity has correlation with the NE for each scenario, when the NE increase, the battery capacity also increase, and when the NE decreases, the battery capacity also decrease. The large NE indicated that the power demand of RO system is greater than the power generated by the RES, therefore in this case the power stored in battery should satisfy as much as possible the power demand.

For each scenario, the hourly freshwater production was calculated and is shown in Fig. 6. For the first scenario, comparing the first half of the year with the second, the gap between needed freshwater and the produced freshwater, is slightly less in the second half of the year, which indicates that the RO system cannot supply sufficient electricity to satisfy the load for those months, therefore an OFW, is needed to overcome this limitation. The total freshwater produced by the RES–BS–RO system during one year of operation is 47,941.87 m³ considering energy losses through electricity transfer and the RO maximum input power and the amount of the minimum outsourced freshwater (52,759.55 m³) in one year of operation. In order to generate more freshwater to satisfy the requirements of FWD, there are two possible solutions: increase the size of the RO system or include another source of storage such as a hydrogen storage system to store the amount of wasted electricity generated by the battery. For the second and third scenarios, the freshwater produced by RO are 88,111.76 m³ and 79,021.23 m³, respectively. Whilst, the outsourced freshwater for water consumer are much less than in scenario one.

4. Economic model of the RES–BS–RO system

The economic model for renewable energies sources considered in this system (solar and wind) are carried out for the three scenarios with assuming that the size of the RES in each scenario is fixed. The subsystems considered in the economic analysis were the RO system, BS system, and OFW, which varies according to the RO size. In addition, the income of freshwater was also considered in order to reduce the cost of the freshwater generation system. The economic model of the RES–BS–RO system and OFW was developed to define the TAC²¹ of the system. The TAC of the combined RES, RO, BS,

and OFW is given in Eq. (1) as follows:

$$TAC_{RES-RO-BS-OFW} = TAC_{PV} + TAC_{WT} + TAC_{RO} + TAC_{BS} + TAC_{OFW} - In_{FW} \quad (1)$$

where the subscript RES–RO–BS–OFW is the combination of PV panel, wind turbine, reverse osmosis desalination system, battery storage, and outsourced freshwater.

The TAC of the RO system considers the RO fresh water production (m³) in one year of operation and the cost of desalination (\$/m³) using Eq. (2).

$$TAC_{RO} = (C_{RO} + C_{mem,RO} + C_{chem,RO} + C_{pre,RO} + C_{int,RO} + C_{man,RO} + C_{main,RO}) \times RO_{prod} \quad (2)$$

The TAC of PV panel, wind turbine, and BS is calculated as the sum of ACC,²² AOMC,²³ and ARC²⁴ using Eq. (3).

$$TAC = ACC + AOMC + ARC \quad (3)$$

The ACC can be calculated by multiplying TCC²⁵ with the AF,²⁶ which shown in Eq. (4).

$$AF = \frac{ir \cdot (1 + ir)^{LC_{sys}}}{(1 + ir)^{LC_{sys}} - 1} \quad (4)$$

where the *ir* interest rate is assumed to be 15%, and *LC_{sys}* is the life time of the system, which is considered to be 20 years.

Considering the life time of several components in the overall system, the replacement of those components is needed during the life cycle of the system. The annual replacement cost (ARC) is calculated by Eq. (5).

$$ARC = C_R \times \left(\frac{LC_{sys}}{LT} - 1 \right) \times AF \quad (5)$$

where the *C_R* is the cost of replacement for each component of the system. Table 5, shows the calculation of TAC of PV panel, wind turbine, and BS in detail.

The TAC of the OFW can be calculated by multiplying the unit cost of water (\$/m³) and the total of outsourced freshwater (m³) during one year of operation as presented in Eq. (6).

$$TAC_{OFW} = \text{Total outsourced freshwater (m}^3\text{)} \times \text{unit cost of water (\$/m}^3\text{)} \quad (6)$$

The income of the freshwater produced by the RO system can be calculated by Eq. (7).

$$In_{FW} = \text{Total freshwater (m}^3\text{)} \times \text{unit price of water (\$/m}^3\text{)} \quad (7)$$

Table 5 shows the economic parameters of RES–RO–BS system and OFW to determine the TAC of each subsystem.

²² Annual capital cost.

²³ Annual operating and maintenance cost.

²⁴ Annual replacement cost.

²⁵ Total capital cost.

²⁶ Amortization factor.

²⁰ Depth of discharge.

²¹ Total annual cost.

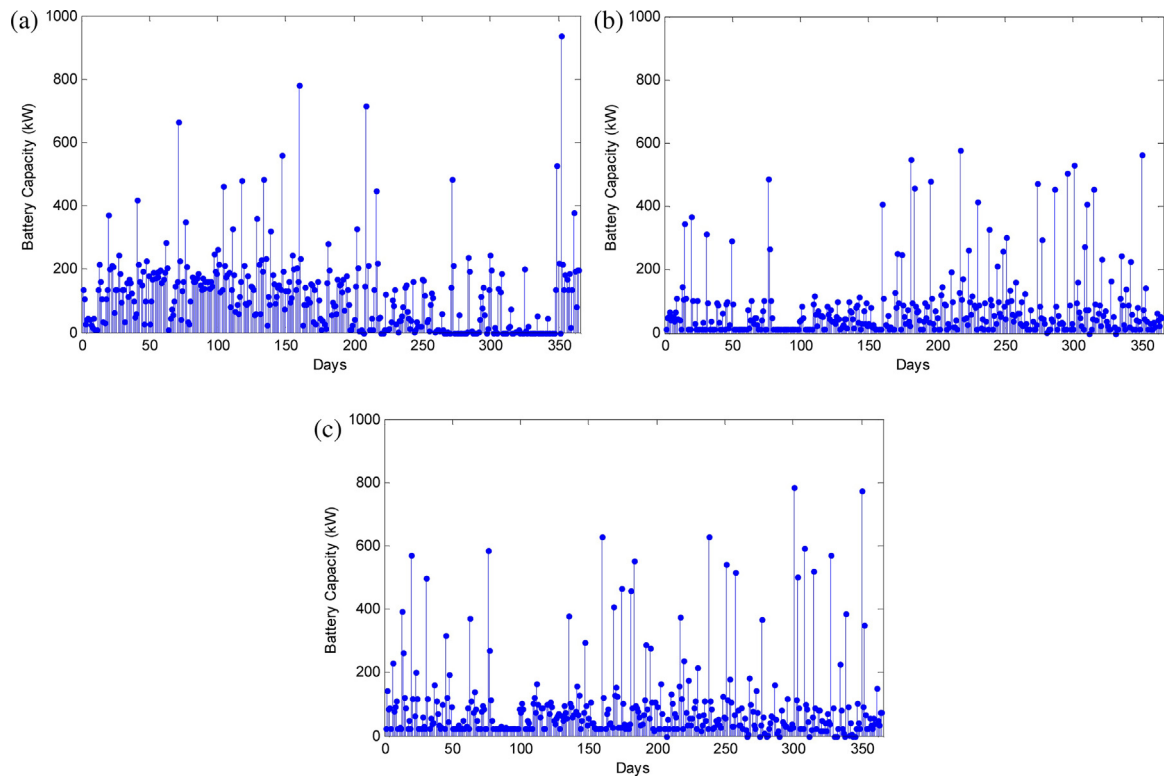


Fig. 5 – The daily battery capacity for three scenarios (a) scenario one, (b) scenario two, (c) scenario three.

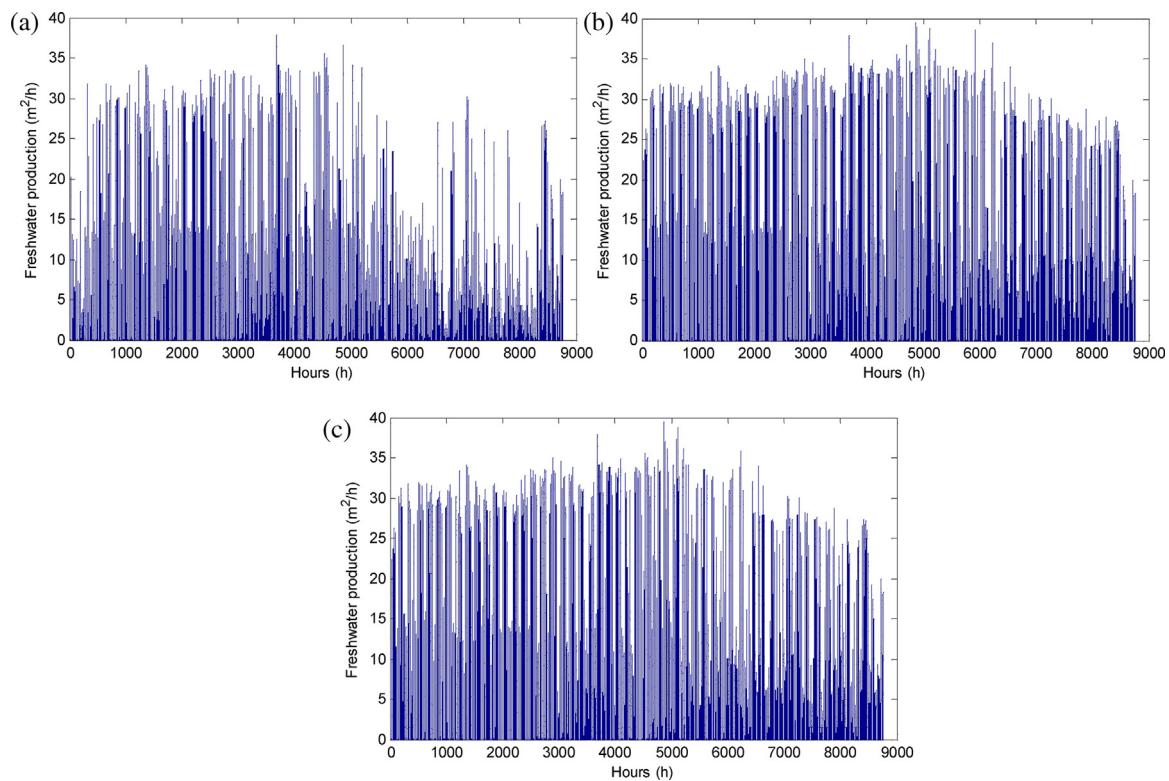


Fig. 6 – The hourly fresh water produced by the RO system of three scenarios (a) scenario one, (b) scenario two, (c) scenario three.

According to the table, the parameter considered for the RO system is the cost of water desalination, based on reference (Karagiannis and Soldatos, 2008). The RES, BS, CC, lifetime, battery replacement, and OAMC were considered based on reference (Janghorban Esfahani, 2015). For OFW, the unit cost of water was considered based on reference (Atikol and Aybar, 2005). The unit price of the freshwater generated by RO was

extracted from (). Table 6 shows the calculation of TAC of PV panel, wind turbine, and BS in detail.

4.1. Sensitivity analysis of the RES–BS–RO system

The sensitivity analysis based on the economic model is conducted to define the appropriate size of the BS system,

Table 5 – Economic parameters of the RES-RO-BS and outsourced freshwater system.

Subsystem	Parameters	Symbol	Value	Unit	Reference
RO	Capital cost	C_{RO}	0.11	\$/m ³	Atikol and Aybar (2005)
	Maintenance and spares	$C_{main,RO}$	0.061	\$/m ³	
	Chemicals cost	$C_{chem,RO}$	0.035	\$/m ³	
	Membrane replacement cost	$C_{mem,RO}$	0.052	\$/m ³	
	Pre-treatment cost	$C_{pre,RO}$	0.035	\$/m ³	
	Manpower cost	$C_{man,RO}$	0.05	\$/m ³	
	Interest cost	$C_{int,RO}$	0.199	\$/m ³	
PV	Capital cost	C_{pv}	350	\$/module	Janghorban Esfahani (2015)
	Replacement cost	$C_{R,pv}$	350	\$/module	
	Lifetime	LT_{pv}	20	Year	
	Operating and maintenance cost (% of capital cost)	$C_{O\&M,pv}$	0	%	
Wind turbine	Capital cost	C_{wt}	150,000	\$/unit	Janghorban Esfahani (2015)
	Replacement cost	$C_{R,wt}$	130,000	\$/unit	
	Lifetime	LT_{wt}	15	Year	
	Operating and maintenance cost	$C_{O\&M,wt}$	2500	\$/year	
BS	Capital cost	C_b	120	\$/kWh	Mahmoudi et al. (2008)
	Replacement cost	$C_{R,b}$	120	\$/kWh	
	Lifetime	LT_b	4	Years	
	Operating and maintenance cost (% of capital cost)	$C_{O\&M,b}$	1	%	
OFW	Unit cost of outsourced fresh water	C_{OFW}	0.7	\$/m ³	Janghorban Esfahani et al. (2016)
Income	Income of RO produce freshwater	IN_{FW}	2.5	\$/m ³	Standard water supply charges, UK

Table 6 – Annual capital cost, annual operating and maintenance cost, and annual replacement cost of PV panel, wind turbine, and battery.

Subsystem	Equation
PV panel	$ACC_{pv} = TCC_{pv} \times AF = C_{pv} \times n_{pv} \times AF$
	$AOMC_{pv} = C_{O\&M,pv} \times TCC_{pv} = C_{O\&M,pv} \times C_{pv} \times n_{pv}$
	$ARC_{pv} = C_{R,pv} \times \left(\frac{LC_{sys}}{LT_{pv}} - 1 \right) \times AF$
Wind turbine	$ACC_{wt} = TCC_{wt} \times AF = C_{wt} \times n_{wt} \times AF$
	$AOMC_{wt} = C_{O\&M,wt} \times TCC_{wt} = C_{O\&M,wt} \times C_{wt} \times n_{wt}$
	$ARC_{wt} = C_{R,wt} \times \left(\frac{LC_{sys}}{LT_{wt}} - 1 \right) \times AF$
Battery	$ACC_b = TCC_b \times AF = C_b \times B_{capacity} \times AF$
	$AOMC_b = C_{O\&M,b} \times TCC_b = C_{O\&M,b} \times C_b \times B_{capacity}$
	$ARC_b = C_{R,b} \times \left(\frac{LC_{sys}}{LT_b} - 1 \right) \times AF$

minimizing the outsourced fresh water. In this study, the size of the RES is assumed to be fixed; for this reason, the sensitivity analysis was carried out considering the RO system, BS, and the OFW for optimization of the system.

The analysis compared different sizes of RO system to determine which one is the best for optimization of the system with a reasonable total annual cost. The sizes of RO system considered were between 10 m³/h and 120 m³/h.

According to Fig. 7 the freshwater produced by the RO system is directly proportional to the size of the RO system. By increasing the RO system size, the freshwater production increases while the OE decreases. For these three scenarios, the freshwater production doesn't show a significant change when the size of RO is greater than 80 m³/h. The BC are raised with the increase of RO size as shown in Fig. 8. For scenario one, the actual BC is increased and is stable when the RO size is greater than 80 m³/h with a constant value of 1170.36 kWh. For scenario two, the maximum actual BC is 724.10 kWh when RO size is equal to 110 m³/h. For scenario three, the actual BC is increased and stable when RO size is more than 90 m³/h with the constant value 980.79 kWh. Considering the income of the freshwater produced by RO system, the TAC of overall sys-

tem for the three scenarios are shown in Fig. 9. The minimum TAC for scenario 1 is 503,159\$/year with a RO size of 40 m³/h. For scenario two, the minimum TAC is 4,033,578\$/year when the RO size is 100 m³/h. For scenario three, is 2,244,208\$/year when the RO size is 120 m³/h. The TAC of scenarios two and three are much higher than scenario one, because of the large fraction of power required from wind turbine and the large capacity of wind turbine to adjust the variance of power demand at each month during the operation year.

Based on the results, this study concluded that the first scenario with 10% of power demand required from wind turbine and 90% of power required from PV panel is shown as the best scenario. The results show that the optimal battery capacity is 1170.36 kWh with a reasonable TAC of 503,159\$/year, which the amount of OFW at 60,096.9 m³/year can produce 40,604.5 m³/year of fresh water using 40 m³/h of the RO system capacity.

5. Conclusions

In this study, the integration of reverse osmosis desalination and hybrid renewable energy (solar and wind) systems with battery storage for the three different scenarios under an energy management strategy has been proposed in order to reduce the power losses of the components in the system as well as reduce the outsourced freshwater using power pinch analysis as a case study in London, UK. The main conclusions are as follows.

1. The proposed energy management strategy showed scenario 1 as the best scenario with an optimum battery capacity of 1170.36 kWh and freshwater production of 40,604.5 m³, which can minimize 60,096.9 m³ of outsourced freshwater with a reasonable total annual cost of 503,159\$/year.
2. A PoCT and SCT were constructed based on the energy management strategy using numerical PoPA to determine, the MOES, AEEND, WE, NE, maximum battery capacity, and

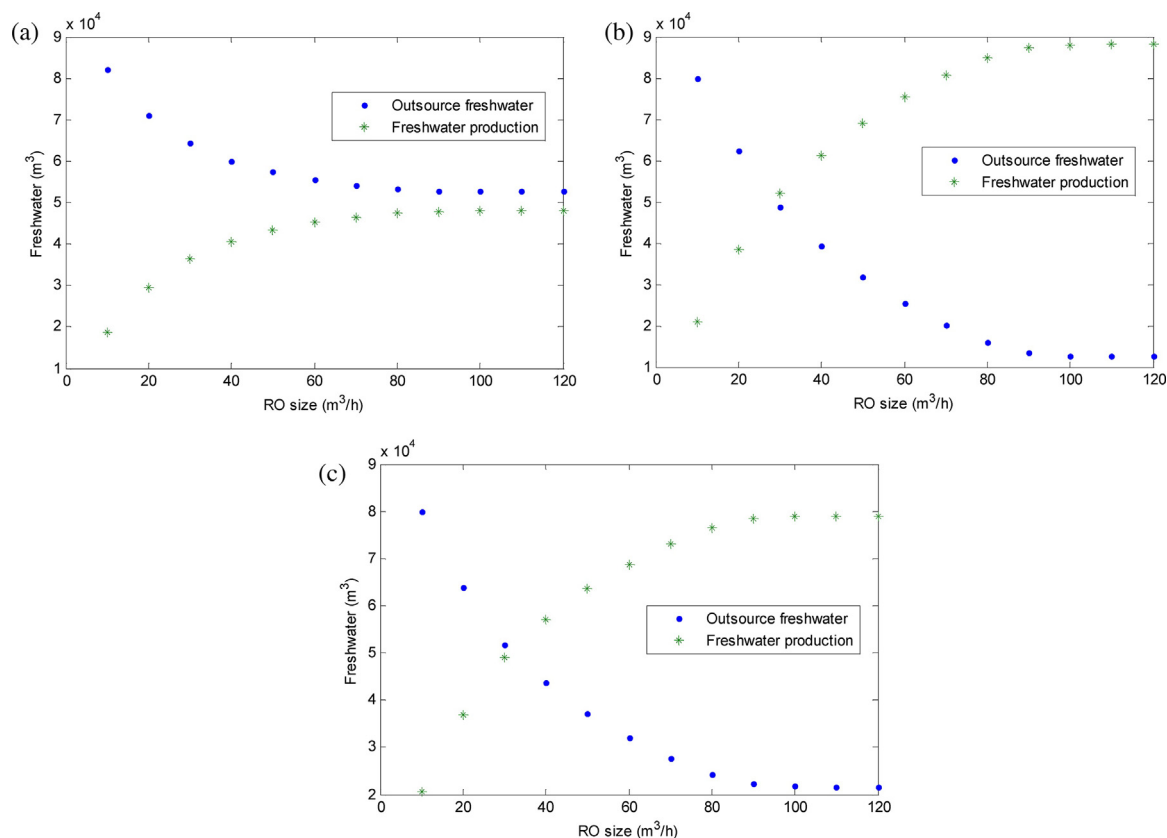


Fig. 7 – Fresh water production by the RO system and outsourced fresh water based on the size of RO system. (a) Scenario one, (b) scenario two, (c) scenario three.

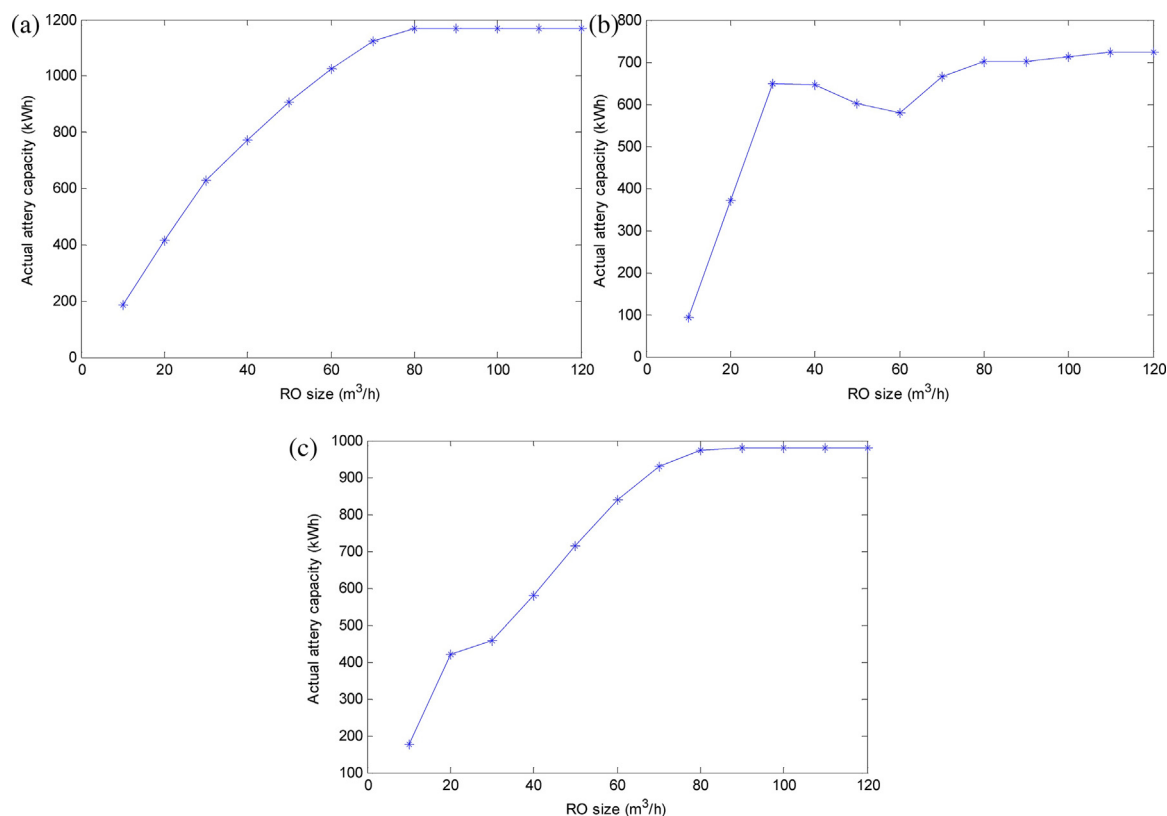


Fig. 8 – Battery capacities for one year of operation based on the RO size. (a) Scenario one, (b) scenario two, (c) scenario three.

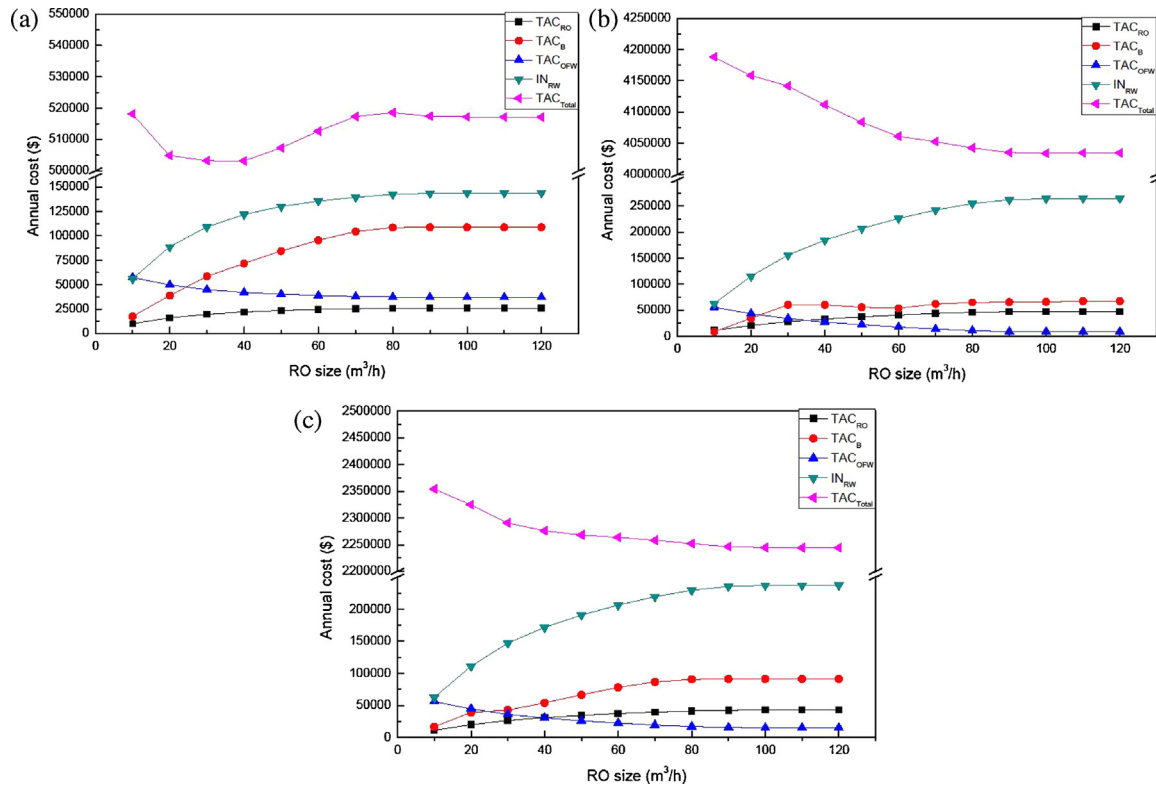


Fig. 9 – TAC of each subsystem in one year of operation based on RO size. (a) Scenario one, (b) scenario two, (c) scenario three.

minimum outsourced freshwater for a normal operation day.

- PoPA was applied based on the SCT to determine the maximum battery capacity, minimum outsourced freshwater, WE, and NE during a normal operation year; a sensitivity analysis based on an economic model was conducted to determine the TAC of the system for a case study in London, UK.
- The analysis of the system suggests that the RES-BS-RO system for the case study has enough potential for integrate a second storage system as a long-term solution to increase the reliability of the system.

Acknowledgement

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Appendix A.

(A.1) Power cascade table calculations

(A.1) Calculation for generated DC electricity

The DC electricity generated by the PV panel was expressed by Hocaoglu et al. (2009) in the form of Eq. (A.1):

$$GP_{DC} = A_{PV} \times \eta_{PV} \times P_f \times \eta_{pc} \times I \times n_{PV} \quad (A.1)$$

where GP_{DC} is the generation of DC electricity (kWh), A_{PV} is the area of the PV panel (m²), η_{PV} is the reference module efficiency, P_f is the packing factor, η_{pc} is the power conditioning efficiency, I is the hourly solar radiation in Wm⁻², and n_{PV} is the number of PV panels, which is 600 for the case study.

Table A1 – PV array, wind turbines, and RO characteristics.

Parameter	Symbol	Unit	Value	Reference
DC source				
Area of PV panel	A_{PV}	m ²	1.63	Janghorban Esfahani et al. (2015)
Module reference efficiency	η_{PV}	–	0.11	Hocaoglu et al. (2009)
Packing factor	P_f	–	0.9	Hocaoglu et al. (2009)
Power conditioning efficiency	η_{pc}	–	0.86	Hocaoglu et al. (2009)
Solar radiation	I	W/m ²	–	
AC source				
Power coefficient of turbine	C_p	–	0.5	Tyagi (2012)
Air density	ρ	kg/m ³	1.225	Tyagi (2012)
Rotor radius	r	m	21	Tyagi (2012)
Wind speed	v	m/s	–	
AD demand				
RO-specific power consumption	γ	kWh/m ³	3	Dashtpour and Al-Zubaidy (2012)

(A.2) Calculation of generated AC electricity

The AC electricity generated by wind turbine was proposed by Tyagi (2012) in the form of Eq. (A.2):

$$GP_{AC} = 0.5 \times C_p \times \rho \times A_{WT} \times v^3 \times n_{WT} \quad (A.2)$$

where GP_{AC} is the generation of AC electricity (kWh); C_p is the power coefficient of the turbine; ρ is the air density (kg/m^3); A_{WT} is the area of the spread of the blade, which is calculated with rotor radius (r) using the equation $A_{WT} = \pi \times r^2$; v is the wind speed in each hour (m/s); and n_{WT} is the number of wind turbines, which is 110 for the case study.

(A.3) Calculation of required AC electricity for RO system

The demand power delivered to the RO system based on water demand and the maximum RO input power (75 kW) can be calculated by Eq. (A.3) (Dashtpour and Al-Zubaidy, 2012).

$$DP_{RO} = \frac{\text{Hourly freshwater demand} \times \gamma}{\text{time interval duration}} \quad (A.3)$$

where DP_{RO} is the demand power delivered to the RO system (kW), and γ is the specific RO power consumption (kWh/m^3).

The parameters of Eqs. (A.1)–(A.3) are summarized in Table A1.

(A.4) Electricity generated by AC

$$\Sigma \text{Electricity source} = GP_{AC} + (GP_{DC} \times \delta) \quad (A.4)$$

where δ , is the convert efficiency.

(A.5) Net AC electricity surplus and deficit

$$\text{NetAC} = \Sigma \text{Generated AC Electricity} - DP_{RO} \quad (A.5)$$

where NetAC , is the net electricity of surplus and deficit of AC (kWh).

(A.6) Pinch point, MOES, and AEEND

$$IE_i = IE_{i-1} + \text{NetAC}_i \quad (A.6)$$

where IE , is the infeasible electricity at each time interval (kWh).

References

- Aissou, S., Rekioua, D., Mezzai, N., Rekioua, T., Bacha, S., 2015. Modeling and control of hybrid photovoltaic wind power system with battery storage. *Energy Convers. Manage.* 89, 615–625, <http://dx.doi.org/10.1016/j.enconman.2014.10.034>.
- Atikol, U., Aybar, Hikmet S., 2005. Estimation of water production cost in the feasibility analysis of RO systems. *Desalination* 184 (1), 253–258, <http://dx.doi.org/10.1016/j.desal.2005.02.065>.
- Bajpai, Prabodh, Dash, Vaishalee, 2012. Hybrid renewable energy systems for power generation in stand-alone applications: a review. *Renew. Sustain. Energy Rev.* 16 (5), 2926–2939, <http://dx.doi.org/10.1016/j.rser.2012.02.009>.
- Borowy, B.S., Salameh, Z.M., 1996. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. *IEEE Trans. Energy Convers.* 11 (2), 367–375, <http://dx.doi.org/10.1109/60.507648>.
- Cherif, Habib, Belhadj, Jamel, 2011. Large-scale time evaluation for energy estimation of stand-alone hybrid photovoltaic–wind system feeding a reverse osmosis desalination unit. *Energy* 36 (10), 6058–6067, <http://dx.doi.org/10.1016/j.energy.2011.08.010>.
- Darton, R.C., 2003. Scenarios and metrics as guides to a sustainable future. *Process Saf. Environ. Prot.* 81 (5), 295–302, <http://dx.doi.org/10.1205/095758203770224333>.
- Rozali, E., Alwi, S.R., Manan, Z.A., Klemes, J.J., Hassan, M.Y., 2013. Process integration of hybrid power systems with energy losses considerations. *Energy* 55, 38–45.
- Elhadidy, M.A., Shaahid, S.M., 2004. Promoting applications of hybrid (wind + photovoltaic + diesel + battery) power systems in hot regions. *Renew. Energy* 29 (4), 517–528, <http://dx.doi.org/10.1016/j.renene.2003.08.001>.
- Janghorban Esfahani, I., 2015. Optimal Design of High Efficient Combined Desalination and Refrigeration System Coupled with CHP and Hybrid Renewable Energy Sources (Unpublished Doctoral Thesis). Kyung Hee University, Global Campus, South Korea.
- Hashim, H., Hudzori, A., Yusop, Z., Ho, W.S., 2013. Simulation based programming for optimization of large-scale rainwater harvesting system: Malaysia case study. *Resour. Conserv. Recycl.* 80, 1–9, <http://dx.doi.org/10.1016/j.resconrec.2013.05.001>.
- Ho, W.S., Hashim, H., Hassim, M.H., Muis, Z.A., Shamsuddin, N.L.M., 2012. Design of distributed energy system through Electric System Cascade Analysis (ESCA). *Appl. Energy* 99, 309–315, <http://dx.doi.org/10.1016/j.apenergy.2012.04.016>.
- Ho, Wai Shin, Khor, Cheng Seong, Hashim, Haslenda, Macchietto, Sandro, Klemeš, Jiří Jaromír, 2013. SAHPPA: a novel power pinch analysis approach for the design of off-grid hybrid energy systems. *Clean Technol. Environ. Policy* 16 (5), 957–970, <http://dx.doi.org/10.1007/s10098-013-0700-9>.
- Ho, Wai Shin, Macchietto, Sandro, Lim, Jeng Shiun, Hashim, Haslenda, Ab Muis, Zarina, Liu, Wen Hui, 2016. Optimal scheduling of energy storage for renewable energy distributed energy generation system. *Renew. Sustain. Energy Rev.* 58, 1100–1107, <http://dx.doi.org/10.1016/j.rser.2015.12.097>.
- Ho, Wai Shin, Tohid, Mohd Zul Waqar Mohd, Hashim, Haslenda, Abdul Muis, Zarina, 2014. Electric System Cascade Analysis (ESCA): solar PV system. *Int. J. Electr. Power Energy Syst.* 54, 481–486, <http://dx.doi.org/10.1016/j.ijepes.2013.07.007>.
- Hocaoğlu, Fatih O., Gerek, Ömer N., Kurban, Mehmet, 2009. A novel hybrid (wind–photovoltaic) system sizing procedure. *Solar Energy* 83 (11), 2019–2028, <http://dx.doi.org/10.1016/j.solener.2009.07.010>.
- Janghorban Esfahani, Iman, Ifaei, Pouya, Kim, Jinsoo, Yoo, ChangKyoo, 2016. Design of hybrid renewable energy systems with battery/hydrogen storage considering practical power losses: a MEPoPA (Modified Extended-Power Pinch Analysis). *Energy* 100, 40–50, <http://dx.doi.org/10.1016/j.energy.2016.01.074>.
- Janghorban Esfahani, Iman, Lee, SeungChul, Yoo, ChangKyoo, 2015. Extended-power pinch analysis (EPoPA) for integration of renewable energy systems with battery/hydrogen storages. *Renew. Energy* 80, 1–14, <http://dx.doi.org/10.1016/j.renene.2015.01.040>.
- Janghorban Esfahani, Iman, Yoo, ChangKyoo, 2016. An optimization algorithm-based pinch analysis and GA for an off-grid batteryless photovoltaic-powered reverse osmosis desalination system. *Renew. Energy* 91, 233–248, <http://dx.doi.org/10.1016/j.renene.2016.01.049>.
- Kalogirou, Soteris A., 2005. Seawater desalination using renewable energy sources. *Prog. Energy Combust. Sci.* 31 (3), 242–281, <http://dx.doi.org/10.1016/j.pecs.2005.03.001>.
- Karagiannis, Ioannis C., Soldatos, Petros G., 2008. Water desalination cost literature: review and assessment. *Desalination* 223 (1), 448–456, <http://dx.doi.org/10.1016/j.desal.2007.02.071>.
- Liu, Wen Hui, Wan Alwi, Sharifah Rafidah, Hashim, Haslenda, Lim, Jeng Shiun, Mohammad Rozali, Nor Erniza, Ho, Wai Shin, 2016. Sizing of Hybrid Power System with varying current type using numerical probabilistic approach. *Appl. Energy* 184, 1364–1373, <http://dx.doi.org/10.1016/j.apenergy.2016.06.035>.
- Ma, Tao, Yang, Hongxing, Lu, Lin, 2014. Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island. *Energy*

- Convers. Manage. 79, 387–397, <http://dx.doi.org/10.1016/j.enconman.2013.12.047>.
- Mahmoudi, H., Abdul-Wahab, S.A., Goosen, M.F.A., Sablani, S.S., Perret, J., Ouagued, A., Spahis, N., 2008. Weather data and analysis of hybrid photovoltaic–wind power generation systems adapted to a seawater greenhouse desalination unit designed for arid coastal countries. *Desalination* 222 (1), 119–127, <http://dx.doi.org/10.1016/j.desal.2007.01.135>.
- Mal, Risha, Prasad, Rajendra, Vijay, Virendra K., 2016. Multi-functionality clean biomass cookstove for off-grid areas. *Process Saf. Environ. Prot.* 104, 85–94, <http://dx.doi.org/10.1016/j.psep.2016.08.003>.
- Mohammad Rozali, Nor Erniza, Wan Alwi, Sharifah Rafidah, Ho, Wai Shin, Abdul Manan, Zainuddin, Klemeš, Jiří Jaromír, 2016. Integration of diesel plant into a hybrid power system using power pinch analysis. *Appl. Therm. Eng.* 105, 792–798, <http://dx.doi.org/10.1016/j.applthermaleng.2016.05.035>.
- Müller-Steinhagen, H., Nitsch, J., 2005. The contribution of renewable energies to a sustainable energy economy. *Process Saf. Environ. Prot.* 83 (4), 285–297, <http://dx.doi.org/10.1205/psep.05084>.
- Prasad, A. Rajendra, Natarajan, E., 2006. Optimization of integrated photovoltaic–wind power generation systems with battery storage. *Energy* 31 (12), 1943–1954, <http://dx.doi.org/10.1016/j.energy.2005.10.032>.
- Dashtpour, R., Al-Zubaidy, S.N., 2012. *Energy efficient reverse osmosis desalination process*. *Int. J. Environ. Sci. Dev.* 3, 339.
- Standard Rates UK. Standard Water Supply Price for the UK. <http://www.anglianwater.co.uk/household/your-account/bills-and-payments/tariffs/standard-rates/>.
- Tyagi, R.K., 2012. *Wind energy and role of effecting parameters*. *Eur. J. Appl. Eng. Sci. Res.* 1, 73–83.
- Wu, K., Zhou, H., An, S., Huang, T., 2015. Optimal coordinate operation control for wind–photovoltaic–battery storage power-generation units. *Energy Convers. Manage.* 90, 466–475, <http://dx.doi.org/10.1016/j.enconman.2014.11.038>.
- Yang, Hongxing, Lu, Lin, Zhou, Wei, 2007. A novel optimization sizing model for hybrid solar–wind power generation system. *Solar Energy* 81 (1), 76–84, <http://dx.doi.org/10.1016/j.solener.2006.06.010>.