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Multi-stage storage optimization based freshwater-power storage cascade analysis for renewable energy-powered desalination system

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ABSTRACT

Freshwater-power pinch analysis (FWaPoPA) as a pinch analysis technique to optimize the design of multi-stage storage systems for the off-grid renewable energy-powered reverse osmosis (RE-RO) systems has been proposed. Herein, FWaPoPA is used to integrate the hybrid water storage tank-battery system to the RE-RO system. The freshwater-power storage cascade table as the FWaPoPA numerical tool is constructed to determine the optimal capacity of the water storage tank and the hybrid water storage tank-battery system, respectively, while minimizing the need for outsourced freshwater. The results of implementing the FWaPoPA tool on three case studies are compared to the RE-RO system without any storage system and with water storage tank designed by freshwater pinch analysis. The results showed that the RE-RO system with an integrated water tank-battery storage system can reduce outsourced freshwater by 30.61%, 2.85% and 28.55% compared to the RE-RO system integrated with water storage tank in case studies 1, 2, and 3, respectively.

Keywords: desalination; freshwater pinch analysis; freshwater-power pinch analysis; reverse osmosis; renewable energy

1. INTRODUCTION

Due to the exploding global population, rapid growth in industry, and increased use of irrigation, the importance and need for high-quality water has significantly increased. The earth contains a vast amount of water, but only three percent is low enough in salinity to be potable, and over two thirds of this three percent is frozen, leaving only one percent of the earth’s water useable [1-3]. Because 97 percent of the water on earth is salt water, desalination of sea and brackish water is essential to provide to many countries especially, those in arid regions that suffer from scarcities of natural freshwater [4, 5]. The most common desalination techniques are reverse osmosis (RO) and thermal desalination including multi-effect evaporation (MEE) and multi-stage flash (MSF). Which process is used is based on the salinity of the water and available energy source. RO requires electric power and thermal desalination systems consume thermal energy, which is conventionally provided by fossil fuels [6-8]. Due to the shortage of fossil fuels and the adverse environmental impacts of their use, such as greenhouse gas (GHG) emissions, the need for renewable energy sources (RES) as an alternative way of powering desalination systems is urgent. Integration of renewable energy sources with desalination systems as renewable energy-powered desalination systems (RE-D) can avoid fossil fuel dependency and the subsequent greenhouse gas emissions, as well as ultimately lower energy and costs and improve efficiency [9, 10].

The greatest problem faced by integration of renewable energy systems (RES) with desalination systems is matching the intermittence of the energy supply with the dynamic water demand [11]. The best solution to overcome the intermittence is to incorporate a storage system into the RE-D system to provide water-on-demand as a highly reliable stand-alone desalination system. Thermal storage systems (TSS) and electricity storage systems (ESS) as well as water storage tanks (WST) are the most common storage devices for RE-D systems. In the integrated RE-D system with energy storage, the energy storage system stores the excess energy from the desalination system, and then delivers it when the energy demands of the desalination system exceed the energy supplied by RES. In the RE-D system integrated with a water storage tank, a water storage tank stores the freshwater produced by the desalination system in excess of the freshwater demand, and then afterward delivers it when demands are high. The RE-D system can be integrated with both energy storage systems (thermal and electrical storage systems) and water storage tanks to increase the reliability of the freshwater supply. Fig. 1 illustrates the coupling of desalination systems (thermal and membrane systems) with renewable energy sources (such as geothermal, biomass, solar, and wind) and storage systems (such as thermal and electrical storage systems).

Recently, several studies designed and evaluated combined RE-D and storage systems [12-23]. Mokheimer et al. [16] mathematically modeled and simulated a hybrid wind/solar powered RO desalination system with battery storage. They optimized the size of the solar photovoltaic (PV) panels, wind turbines and batteries for a constant RO load of 1 -kW by minimizing the unit product cost of freshwater. Also, Al-Nory and El-Beltagy [19] proposed an energy management approach based on a mathematical optimization model for integration of renewable energy with a power and water cogeneration system. They solved their model by minimizing the total costs of power and freshwater. Spyrou and Anagnostopoulos [20] developed a numerical algorithm to investigate and optimize a reverse osmosis desalination unit powered by hybrid wind/solar power generation and a pumped storage unit as the energy storage system. They optimized the system based on various objective functions such as minimization of freshwater production cost and maximization of water demand satisfaction. Sassi and Mujtaba [22] optimized the design and operation conditions of an RO system coupled with a water storage tank. They used the water storage tank to increase the operational flexibility and availability of freshwater with respect to dynamic freshwater load demand. Elkader [23] designed a three stage multi-effect humidification-dehumidification process with an energy storage system. They showed that the implementation of the energy storage system can increase the water production by 13.5%. Thus, mathematical modeling and non-visual methods have been widely used to design and optimize storage systems for RE-D systems.

Pinch analysis (PA), an alternative to mathematical modeling, has also been used to optimize the design of conservation networks of resources such as heat [24], combined heat and power [25], mass [26], water [27], carbon [28], properties [29], hydrogen [30], power [31], and freshwater [32]. Unlike mathematical modeling, pinch analysis use both visual and numerical tools, thereby proving better insights into the models.

Recently, pinch analysis has been used by researchers for integration of renewable energy systems with battery storage. For example, Bandyopadhyay [33] determined the optimal size of the battery for an off-grid PV/battery system based on pinch and design space analyses by constructing a grand composite curve. The power pinch analysis (PoPA) was also used by Alwi et al. [31]. They introduced power composite curves as graphical tool to determine the minimum outsourced electricity needed for an off-grid hybrid power system with a battery bank. Later, Rozali et al. [34] implemented numerical tools of the PoPA including a power cascade analysis and storage cascade table to determine the minimum amount of outsourced electricity needed and optimize the size of the battery bank for a hybrid power system. Following on Alwi et al. [31] and Rozali et al.'s [34] research, Janghorban Esfahani et al. [35] extended the PoPA to optimize the design of a hydrogen storage system as a secondary storage system for an off-grid hybrid power system with a battery bank. They used graphical and numerical tools to determine the minimum requirements of outsourced electricity and the optimal size of the hydrogen storage system components. Janghorban Esfahani et al. [32] proposed freshwater pinch analysis (FWaPA) for retrofitting the off-grid battery less photovoltaic-powered reverse osmosis system with water storage tank to minimize the required outsourced freshwater. They introduced freshwater composite curve and freshwater storage cascade table as the graphical and numerical tools of the FWaPA to determine the optimal delivered electricity to the RO system and water storage tank capacity. Altogether, these studies show that pinch analysis has been used only to integrate RE-D systems with water storage tank and has not yet been used to integrate RE-D systems with multi-storage system as the most reliable system to supply freshwater.

This study utilizes freshwater-energy pinch analysis (FWaEPA) to optimize the design of a water-energy storage system for an off-grid RE-D system. PoPA, as presented by Alwi et al. [31], and EPoPA and FWaPA as presented by Janghorban Esfahani et al. [32, 34] are the basis of FWaEPA. FWaEPA is introduced to store excess energy produced by RES that cannot immediately be used by the desalination system. The energy is then delivered to the desalination system when outsourced energy is needed. Excess freshwater produced by the desalination system is then stored in a water storage tank and delivered to consumers when freshwater is needed. Based on type of the RE-D system, the FWaEPA is also known as a freshwater-heat pinch analysis (FWaHPA) for integration of thermal storage system and known as a freshwater-power pinch analysis (FWaPoPA) for integration of an electricity storage system to the RE-D system. In this study, FWaEPA is implemented as a FWaPoPA to integrate a water storage tank and an electrical energy storage system to the RE-D system with RO as the desalination system (RE-RO). The FWaPoPA numerical tool such as freshwater-power storage cascade table (FWaPoSCT) is introduced to determine 1) the minimum outsourced freshwater needed during the first operation day, 2) available excess freshwater and electricity for the next day, 3) the minimum outsourced freshwater needed during a normal operation day, 4) wasted electricity, and 5) the optimal size for the water storage tank and battery bank.

This study consists of four major parts. First, three possible case studies are extracted based on case studies presented by Alwi et al. [31]. Second, a freshwater storage cascade table (FWaSCT, based on FWaPA [32], is constructed. Third, a freshwater-power storage cascade table (FWaPoSCT) is constructed to optimize the size of the water tank and battery bank to minimize the requirements for outsourced freshwater. Fourth, the results of the FWaPA [32] and the FWaPoPA for the three case studies are compared to define the best storage system configuration for the RE-RO system.

2. METHODOLOGY

2.1 RE-RO-WSTB system description

Fig. 2 shows the renewable energy-powered RO desalination with a water storage tank and battery system (RE-RO-WSTB). This system comprises renewable energy sources including biomass, solar panels, and wind turbines as well as an RO desalination system with water storage tank and battery system. The electricity is generated by RES and then delivered to the RO system where seawater is separated into freshwater and brine. The freshwater is subsequently delivered to the freshwater load demand while the brine is deposited back into the sea. As shown in Fig. 2, the freshwater produced by the RE-RO system is stored in the water storage tank when it is not immediately needed and is then delivered to the consumer when the RE-RO freshwater production is less than the freshwater demand. The excess electricity is stored in the battery that can not immediately be used by RO system and then delivered to the RO system when outsourced electricity is needed. Therefore, the RE-RO-WSTB system can take full advantage of times when the RES generates a large amount of energy. Energy storage, in turn, leads to less of a need for outsourced electricity and freshwater.

Three possible case studies for daily operation of the system are presented in Tables 1 and 2. These case studies were extracted from the case studies presented by Alwi et al. [31]. Table 1 presents the power and electricity generated by three renewable energy sources including solar PV panels, wind turbines, and biomass. Table 2 shows the freshwater demand loads of five consumers. The KRO-40-MCS model RO desalination system manufactured by KROSYS is considered. A maximum input power of 75 kW was used with a power consumption of 9 kWh/m^3.

2.2 Freshwater pinch analysis (FWaPA)

The freshwater pinch analysis (FWaPA), and its associated numerical tool, freshwater storage cascade table (FWaSCT) was used to integrate the water storage tank into the RE-RO system to calculate the outsourced freshwater and the wasted RE electricity in each time interval during first operation day and a normal operation day, and to determine the optimal size of the water storage tank to minimize the need for outsourced freshwater. The steps to construct the FWaSCT for case study 1, presented in Table 3, are described as follows [32]:

Step 1. Calculation of net freshwater surplus/deficit

In this step, the freshwater surplus and freshwater deficit are calculated for each time interval as follow:

1) Definition of time intervals

The time interval numbers are presented in the first column of Table 3. The second column of Table 3 presents the time from ‘0’ to ‘24’ hours, with midnight corresponding to hour 0, and the third column shows the time duration between the two abutting time intervals [32].

2) Calculation of power rating and electricity generation

The summation of power rating (kW) and electricity generation (kWh) by RES in each time-interval are calculated by Eqs. (1) and (2) [32].

$$Power\ rating_n = \left(\sum_{k=1}^{3} Power\ rating \right)_n \quad (kW) \tag{1}$$

$$Electricity\ generation_n = Power\ rating_n \times time\ interval\ duration_n \quad (kWh) \tag{2}$$

where, n is number of time-intervals, $k$is the number of renewable energy sources including solar, wind, and biomass. The freshwater demand at each time-intervals is based on data presented in Table 2. For each time interval, the sum of power rating is presented in column 4, and the sum of electricity generation is presented in column 5.

3) Calculation of power delivered to RO and wasted electricity

The electricity generated by RES in each time interval, presented in column 5, is delivered to the RO system to produce freshwater. The electricity can be delivered to the RO system up to its maximum input power, which is considered to be 75 kW in this study. Therefore, the delivered power to the RO system is determined by Eq. (3) and is presented in column 6 [32].

$$\begin{array}{lll} Delivered\ power\ to\ RO_n = Power\ rating_n & if & Power\ rating_n \leq 75 \\ Delivered\ power\ to\ RO_n = 75 & if & Power\ rating_n > 75 \end{array} \quad (3)$$

The excess electricity that cannot be delivered to the RO system is wasted. The wasted electricity in each time interval is calculated by Eq. (4) and is presented in column 7 [32].

$$Wasted\ Electricity_n = Electricity\ generation_n - \left(delivered\ power\ to\ RO_n \times timeinterval\ duration_n\right)$$
(4)

4) Calculation of net freshwater surplus/deficit

The freshwater produced by the RO system in each time interval with respect to the power delivered to the RO (presented in column 6) is calculated by Eq. (5) and shown in column 8 [32].

$$Freshwater\ production_n = \frac{Delivered\ power\ to\ RO_n \times time\ interval\ duration}{RO\ power\ consumption} \quad (m^3) \qquad (5)$$

The RO power consumption is considered here to be 9 m^3/kWh.

The freshwater demand in each time interval is determined by Eq. (6) [32]; it is the sum of the freshwater demands for all the consumers and is presented in column 9 of Table 2.

$$Freshwater\ demand_n = \left(\sum_{i=1}^{k} Freshwater\ demand_i\right)_n \times time\ interval\ duration_n \quad (m^3) \qquad (6)$$

where *i* is an individual consumer and *k* is the total number of freshwater consumers.

Net freshwater surplus or net freshwater deficit in each time interval is calculated by subtracting freshwater demand from freshwater production (Eq. (7)) [32]; this is presented in column 10.

$$FWaS / D_n = Freshwater\ production_n - Freshwater\ demand_n \quad (m^3) \qquad (7)$$

where FWaS/D is freshwater surplus or deficit in the n^{th} time interval. A positive value of FWaS/D is the freshwater surplus (FWaS) that can be stored in the water storage tank, while a negative value indicates a freshwater deficit (FWaD) that must be extracted from the water storage tank or provided by outsourced freshwater.

Step 2. Calculation of water storage capacity and outsourced freshwater

The optimal capacity of the water storage tank, the volume of water in tank, and the volume of outsourced freshwater during each time interval of the first operation day and a normal operation day are calculated as follows [32]:

- First operation day

The net freshwater surplus and deficit, presented in column 10, is cumulatively cascaded down with an assumption of zero freshwater in the water storage tank at time 0. A positive value for cumulative freshwater is shown as the volume of water in the storage tank (column 11) and the negative values are the outsourced freshwater needed for each time interval (column 12). It can be seen in column 12 that 23.33 m^3 outsourced freshwater is required during the fourth time interval, with an average flow rate of 2.92 m^3/h (calculated by Eq. (8) [32]) and presented in column 13.

$$outsourced\ freshwater\ flow\,rate_n = \frac{outsourced\ freshwater_n}{time\ interval_n} \quad (m^3 / h) \qquad (8)$$

Also, the sum of all the outsourced freshwater needed during the first operation day (Eq. (9)) can be defined as the minimum amount of freshwater that should be available in the water storage tank at the start-up of the system to prevent the need for outsourced freshwater on the first operation day [32].

$$minimum\ initial\ \ freshwater = \sum_{n=1}^{k} outsourced\ \ freshwater_n \tag{9}$$

where n is number of the time interval and k is the number of time intervals in one 24-hour period.

Similar to case study 1, FWaSCTs are constructed for case studies 2 and 3 as presented in Tables A-1 and A-2 of Appendix A. For case study 2, as presented in column 12 of Table A-1, 15.33 m^3 of freshwater is needed initially in the water storage tank on the first operation day, or a freshwater flow rate of 1.92 m^3/h is required from 10 am to 6 pm. Also, for case study 3, as presented in column 12 of Table A-2, the initial freshwater required in the water storage tank is 24.33 m^3, or a flow rate of 3.04 m^3/h, is needed during the fourth time interval.

-Normal operation day

For the normal operation day, the available freshwater in the water storage tank at the end of the first operation day is used for the next operation day.

For case study 1, as can be seen in column 11 of Table 3, 8 m^3 of freshwater is available in the water storage tank at the end of the first operation day. The net freshwater surplus/deficit is cumulatively cascaded down with 8 m^3 of freshwater at time ‘24’ at the end of the day, which can be used during the next operation day (positive values are presented in column 14 and negative values are presented in column 15). It can be seen that, in the normal operation day, the system needs 15.33 m^3 freshwater during 10 am to 6 pm, and thus an average flow rate of 1.92 m^3/h. Based on these data, a water storage tank with a capacity of 31.33 m^3 is appropriate to store freshwater.

Similar to case study 1, case studies 2 and 3 required a freshwater storage capacity of 14 m^3 and 11 m^3, respectively, at the end of the first operation day (column 14 of Tables A-1 and A-2). It can be seen that for case studies 2 and 3, outsourced freshwater of 1.33 m^3 and 13.33 m^3 with an average flow rate of 0.17 m^3/h and 1.67 m^3/h, respectively, are required during normal operation days.

2.3 Freshwater-power pinch analysis (FWaPoPA)

In this section, the freshwater-power pinch analysis is introduced to optimize the design of a freshwater-power storage system including a water storage tank and a battery bank for an off-grid RE-RO system to minimize the need for outsourced freshwater. The freshwater-power storage cascade table (FWaPoSCT) is constructed as a numerical tool of the FWaPoPA to determine 1) the minimum outsourced freshwater needed during the first operation day, 2) available excess freshwater and electricity for the next day, 3) the minimum outsourced freshwater needed during a normal operation day, 4) wasted electricity, and 5) the optimal size for the water storage tank and battery bank. The steps to construct of the FWaPoSCT are described as follows:

2.3.1 Freshwater-power storage cascade table (FWaPoSCT)

The FWaPoSCT for case study 1 is presented in Table 4, for case study 2 the results are in Tables A-3 and A-4, and for case study 3 the results are in Table A-5. The constructions of the FWaPoSCT for the 3 case studies are explained as follows:

2.3.1.1 Case study 1

The FWaPoSCT for case study 1 is constructed by the following steps:

Step 1. Calculation of power rating and electricity generation

Columns 1 to 3 of Table 4a present the time-interval number, the time, and time interval duration. The power rating and electricity generation by RES in each time-interval are calculated by Eqs. (1) and (2) and presented in columns 4 and 5, respectively.

- First operation day

Step 2. Calculation of net freshwater surplus/deficit

The freshwater surplus and deficit during each time interval is calculated with following steps:

1) Calculation of freshwater production and freshwater demand

Freshwater production by the RE-RO system and the freshwater demand in each time interval are determined as described in section 2.2, step 1.

2) Calculation of delivered power and electricity to RO and battery

The delivered power from RES to the RO system in each time interval is calculated based on step 1 described in section 2.2. The surplus electricity that cannot be delivered to the RO system is stored to the battery bank. The delivered electricity to the battery bank in each time interval is calculated by Eq. (10) and shown in column 7.

$$Electricity\ to\ battery_n = Electricity\ generation_n - \left(delivered\ \ power\ to\ RO_n \times time\ interval\ duration_n\right) \quad (10)$$

3) DETERMINATION OF ELECTRICITY STORED IN BATTERY

In order to determine the amount of electricity stored in the battery at each time interval, the electricity in the battery is cumulatively cascaded down from time ‘0’ to ‘24’, where the delivered power to the RO is increased up to its maximum input power (column 7 of Table 4a). Therefore, it can be seen in column 9 of Table 4a that during fifth and sixth time intervals, the delivered power to the RO system is increased from 60 kW to 75 kW. There is 90 kWh available in the battery at the end of the fifth interval and 30 kWh electricity available in the battery at the end of the sixth interval.

3) Calculation of net freshwater deficit/surplus

The freshwater production and freshwater demand in each time interval are calculated by Eqs. (5) and (6) described in section 2.2. The freshwater surplus and deficit in each time interval during the first operation day is determined by Eq. (7) and presented in column 12.

Step 3. Calculation of water storage capacity and requirements for outsourced freshwater

In this step, the volume of water in the storage tank and the volume of outsourced freshwater are determined during the first operation day for each time interval. The net freshwater surplus and deficit is cumulatively cascaded down with the assumption that there is zero freshwater at time ‘0’ in the water storage tank (column 12). A positive value of freshwater is shown in column 13 as the volume of water in the storage tank and a negative value in column 14 indicates the volume of freshwater that needs to be outsourced for each time interval.

As presented in column 14, 23.33 m^3 of outsourced freshwater is required during the peak usage time (from 10 am to 6 pm), with an average flow rate of 2.92 m^3/h (calculated by Eq. (8)). Alternatively, one can supply 23.33 m^3 of freshwater initially in the water storage tank for the first operation day to avoid the need for outsourced water (Eq. (9)).

-Normal operation day

The available electricity in the battery and the available freshwater in the water storage tank at the end of the first operation day can be used the next day.

For case study 1, as presented in column 8 of Table 4a, 30 kWh electricity is available in the battery at the end of the first day. This amount of electricity is cumulatively cascaded down in the next operation day and shown in column 16 of Table 4b, where the delivered power to the RO (column 17) is maximized. The freshwater production, freshwater demand, and net freshwater surplus/deficit at each time interval are calculated by Eqs. (5), (6), and (7) and shown in columns 18, 19, and 20, respectively. The net freshwater surplus/deficit is cumulatively cascaded down with 18 m^3 freshwater available in the water storage tank at time 0 (column 20). Positive values in column 21 indicate the volume of water in the storage tank and negative values in column 22 indicate the requirement for outsourced freshwater. It can be seen that, in a normal operation day, the system needs 2 m^3 freshwater during 10 am to 6 pm, with an average flow rate of 0.25 m^3/h. The maximum battery usage was calculated to be 120 kWh (column 16) and the maximum volume of water in the storage tank was 44.67 m^3. Thus, these values define the appropriate minimum capacities of the battery and water storage tank to minimize the need for outsourced freshwater.

2.3.1.2 Case study 2

The FWaPoSCT for case study 2 is shown in Table A-3. It is constructed with steps 1 to 3 presented in section 2.3.1.1. It can be seen in Table A-3a that, in the first operation day, 15.33 m^3 of outsourced freshwater is needed with an average flow rate of 1.92 m^3/h during 10 am to 6 pm. If 15.33 m^3 can be in the water storage tank for the first operation day, no additional freshwater would be required.

For a normal operation day, 30 kWh electricity is available in the battery at the end of the first operation day (column 16 of Table A-3a). This electricity is cumulatively cascaded down to the next operation day (column 16) with the maximum power delivered to the RO system (column 17). The net freshwater surplus/deficit at each time interval (column 20) is calculated similar to case study 1. The net freshwater surplus/deficit is cumulatively cascaded down, accounting for the 24 m^3 freshwater available in the water storage tank at the end of the first operation day. Positive values of cumulative water in the water storage tank are shown in column 21 and negative values in column 22 indicate the need for outsourced freshwater. In this case, there is no need for any outsourced freshwater, as the values of column 22 are zero. It can be seen in column 21 that the volume of stored freshwater at the end of the normal operation day (36 m^3) is greater than the volume of stored freshwater at the beginning of the day (24 m^3). Thus, 12 m^3 of excess freshwater was produced by the RO system and stored in the tank. Because RO consumes 9 kWh/m^3 power to the produce 12 m^3 excess freshwater, the RO system consumes 108 kWh of electricity total from the battery or directly from the RES. Therefore, the excess freshwater production leads to increased capacity requirements for the battery and increased operating costs, leading to an overall increase in the freshwater production cost. To lessen waste, the amount of electricity delivered to the battery can be decreased. One can calculate how much energy and water needs to be available at the beginning of a normal operation day to prevent the need for outsourced water, and then eliminate excess freshwater production. Specifically, the FWaPoSCT is modified by reducing the amount of energy stored in battery to 12 kWh. The modified FWaPoSCT for case study 2 is shown in Table A-4. Due to reduced amount of energy stored in the battery (only 12 kWh during the second time interval), there is more RES electricity waste during other time intervals. The wasted electricity in each time interval is calculated by Eq. (11) and shown in column 23 of Table A-4b.

$$Wasted\ electricity_n = \frac{Power\ rating_n - \left(Delivered\ \ power\ to\ RO + Power\ to\ battery\right)_n}{timeinterval\ duration_n} \qquad (11)$$

The sum of the wasted electricity during all time intervals is 33 kW. The maximum water storage of 46.67 m^3 (column 21) and the maximum battery requirements of 12 kWh (column 16) are defined as the minimum capacities for the water storage tank and the battery to minimize the need for outsourced freshwater.

2.3.1.3 Case study 3

FWaPoSCT of case study 3 is constructed and presented in Table A-5 based on steps 1 to 3 described in section 2.3.1.1. For the first operation day (column 14 of Table A-5a), the initial freshwater required in the water storage tank is 24.33 m^3, or an average flow rate of 3.04 m^3/h of freshwater is needed during the fourth time interval. For a normal operation day, similar to case study 1, the 30 kWh of electricity stored in the battery and 21 m^3 of freshwater stored in the water storage tank at the end of the first operation day is used during the next operation day. Columns 16 to 23 of Table A-5b are constructed based on the steps described in section 2.3.1.1 (similar of columns 16 to 23 of Table 4a). As shown in column 13 of Table A-5a, there is no need for any outsourced freshwater and there is no excess freshwater production. The largest volume in the water storage tank (51.67 m^3, column 22) and the largest amount of electricity in the battery (120 kWh, column 16) define the minimum recommended capacities for the water storage tank and the battery bank.

2.4 Comparisons of FWaPA and FWaPoPA

Table 5 shows the results obtained by implementation of FWaPA and FWaPoPA with an RE-RO system without any storage for the three case studies. As shown in Table 5, the RE-RO system needs a total of 46.7 m^3 of freshwater for case studies 1 and 2 and 51.7 m^3 freshwater for case study 3 during the first and normal operation days. Also, the RE-RO system generates 101, 137, and 119 kW excess power for case studies 1, 2, and 3, respectively, during both the first and normal operation days.

It can be seen in Table 5 that the RE-RO system with the water storage tank (RE-RO-WST), designed with FWaPA, would require 23.33, 15.33, and 24.33 m^3 freshwater in the water storage tank for case studies 1, 2, and 3, respectively, at the start of the first operation day. The use of a water storage tank that has a capacity of at least 31.33, 45.33, and 38.33 m^3 decreases the need for outsourced freshwater for case studies 1, 2, and 3, respectively, during a normal operation day. As presented in Table 5, 35 kW of power is wasted during the first operation day and normal operation days in all three case studies.

For the RE-RO-WSTB system designed by FWaPoPA, 23.33, 15.33, and 24.33 m^3 of outsourced freshwater is required for case studies 1, 2, and 3, respectively, during both the first operation day and normal operation days. Water storage tanks of 44.67, 46.67, and 51.67 m^3 and battery banks with capacities of 120, 12, and 120 kWh are determined for case studies 1, 2, and 3, respectively. It can be seen that 33 kW of power is wasted in case study 1, while there is not any wasted power in case studies 2 and 3.

Fig. 3 shows the requirements for outsourced freshwater of RO-RE-WST and RO-RE-WSTB systems during the first operation day and normal operation days compared to the RE-RO system without any water or electricity storage. It can be seen that both systems decrease the need for outsourced freshwater by 50.04%, 67.17%, and 47.9% during the first operation day for case studies 1, 2, and 3, respectively. This means that, for the three case studies, the battery bank has no effect on the need for outsourced freshwater during the first operation day. For a normal operation day, the water storage tank reduces the need for outsourced freshwater by 67.1%, 97.15, and 71.45% for case studies 1, 2, and 3, respectively, compared to the base system. At the same time, using a battery in addition to the water storage tank reduces the need for outsourced freshwater by 95.71% for case study 1 and eliminates it for case studies 2 and

3 compared to the RE-RO system. Thus, the battery can reduce the need for outsourced freshwater during normal operation days in some cases.

Fig. 4 shows the wasted power of the RE-RO-WST, RE-RO-WSTB compared to the RE-RO systems. The RE-RO-WST system can save 65.34, 74.45, and 70.59% power in case studies 1, 2, and 3, respectively, compared to the RE-RO system during the first operation day and normal operation days. As presented in Fig. 4 the wasted power is more decreased by adding battery to the RE-RO-WST system as the RE-RO-WSTB system can save 67.32% in case study 2 compared to the base system and there is no any wasted power for case studied 1 and 3 during first and normal operation days.

3. CONCLUSIONS

In this study, the freshwater-power pinch analysis (FWaPoPA) was used to optimize the design of multi-stage storage systems for a renewable energy-powered RO desalination system. The freshwater storage cascade table (FWaSCT) and freshwater-power storage cascade table, based on FWaPA, and (FWaPoSCT), based on FWaPoPA, were constructed to numerically determine the optimal size of the water storage tank and battery bank so that the need for outsourced freshwater is minimal. The system designed by FWaPA technique can reduce the need for outsourced freshwater by 67.1, 97.15, and 71.45% for case studies 1, 2, and 3, while the system designed by FWaPoPA technique can reduce 95.71% for case study 1 and completely eliminate the need for outsourced freshwater in case studies 2 and 3. The proposed FWaPoPA not only offer an important method for integrating multi-storage systems into the RE-RO system, but also provide a robust tool for integrating any storage system (e.g., a thermal storage system) with renewable energy-powered desalination systems.

Appendix A

Table A-1 Freshwater storage cascade table (FWaSCT) for case study 2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
										First operation day			Normal operation day		
Time-Interval Number (n)	Time (h)	Time Interval (h)	Sum Power rating (kW)	Sum electricity generation (kWh)	Delivered power to the RO (kW)	Wasted electricity (kWh)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)=initial value of water storage tank	Outsourced freshwater (m^3/h)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)	Outsourced freshwater (m^3/h)
	0									0			14.00		
1	2	2	60	120	60	0.00	13	8.0	5.33	5.33	0.00	0.00	19.33	0.00	0.00
2	8	6	80	480	75	30.00	50	24.0	26.00	31.33	0.00	0.00	$\boxed{45.33}$	0.00	0.00
3	10	2	100	200	75	50.00	17	26.0	-9.33	22.00	0.00	0.00	36.00	0.00	0.00
4	18	8	80	640	75	40.00	67	104.0	-37.33	0.00	-15.33	-1.92	0.00	-1.33	-0.17
5	20	2	60	120	60	0.00	13	10.0	3.33	3.33	0.00	0.00	3.33	0.00	0.00
6	24	4	60	240	60	0.00	27	16.0	10.67	14.00	0.00	0.00	14.00	0.00	0.00

The value shown in box presented in column 14 is selected as the optimal volume of water storage tank

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Table A-2 Freshwater storage cascade table (FWaSCT) for case study 3

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
										First operation day			Normal operation day		
Time-Interval Number (n)	Time (h)	Time Interval (h)	Sum Power rating (kW)	sum electricity generation (kWh)	delivered power to the RO (kW)	wasted electricity (kWh)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit, (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)=initial value of water storage tank	Outsourced freshwater (m^3/h)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)	Outsourced freshwater (m^3/h)
	0									0			11.00		
1	2	2	60	120	60	0.00	13	9.0	4.33	4.33	0.00	0.00	15.33	0.00	0.00
2	8	6	80	480	75	30.00	50	27.0	23.00	27.33	0.00	0.00	$\boxed{38.33}$	0.00	0.00
3	10	2	100	200	75	50.00	17	27.0	-10.33	17.00	0.00	0.00	28.00	0.00	0.00
4	18	8	80	640	75	40.00	67	108.0	-41.33	0.00	-24.33	-3.04	0.00	-13.33	-1.67
5	20	2	60	120	60	0.00	13	11.0	2.33	2.33	0.00	0.00	2.33	0.00	0.00
6	24	4	60	240	60	0.00	27	18.0	8.67	11.00	0.00	0.00	11.00	0.00	0.00

The value shown in box presented in column 14 is selected as the optimal capacity of water storage tank

Table A-3a Freshwater-power storage cascade table (FWaPoSCT) for case study 2 (First operation day)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							First operation day							
Time-Interval Number (n)	Time (h)	Time Interval (h)	Sum Power rating (kW)	Sum electricity generation (kWh)	Delivered power to the RO (kW)	Electricity to battery (kWh)	Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)=initial value of water storage	Outsourced freshwater (m^3/h)
	0						0					0		
1	2	2	60	120	60	0	0	60	13	8.0	5.33	5.33	0.00	0.00
2	8	6	80	480	75	30	30	75	50	24.0	26.00	31.33	0.00	0.00
3	10	2	100	200	75	50	80	75	17	26.0	-9.33	22.00	0.00	0.00
4	18	8	80	640	75	40	120	75	67	104.0	-37.33	0.00	-15.33	-1.92
5	20	2	60	120	60	0	90	75	17	10.0	6.67	6.67	0.00	0.00
6	24	4	60	240	60	0	30	75	33	16.0	17.33	24.00	0.00	0.00

Table A-3b Freshwater-power storage cascade table (FWaPoSCT) for case study 2 (Normal operation day)

16	17	18	19	20	21	22
Normal operation day						
Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)
30					24.00	
0	75	16.67	8.0	8.67	32.67	0.00
30	75	50.00	24.0	26.00	58.67	0.00
80	75	16.67	26.0	-9.33	49.33	0.00
120	75	66.67	104.0	-37.33	12.00	0.00
90	75	16.67	10.0	6.67	18.67	0.00
30	75	33.33	16.0	17.33	36.00	0.00

Table A-4a Modified freshwater-power storage cascade table for case study 2 (First operation day)

1	2	3	4	5	7	8	9	10	11	12	13	14	15
						First operation day							
Time-Interval Number (n)	Time (h)	Time Interval (h)	Sum Power rating (kW)	Sum electricity generation (kWh)	Electricity to battery (kWh)	Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)=initial value of water storage	Outsourced freshwater (m^3/h)
	0					0					0		
1	2	2	60	120	0	0	60	13	8.0	5.33	5.33	0.00	0.00
2	8	6	80	480	12	12	75	50	24.0	26.00	31.33	0.00	0.00
3	10	2	100	200	0	12	75	17	26.0	-9.33	22.00	0.00	0.00
4	18	8	80	640	0	12	75	67	104.0	-37.33	0.00	-15.33	-1.92
5	20	2	60	120	0	0	66	15	10.0	4.67	4.67	0.00	0.00
6	24	4	60	240	0	0	60	27	16.0	10.67	15.33	0.00	0.00

Table A-4b Modified Freshwater-power storage cascade table for case study 2 (Normal operation day)

16	17	18	19	20	21	22	23
Normal operation day							
Electericity stored in the battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Valume of water in tank (m^3)	Outsourced freshwater (m^3)	Wasted electricity (kW)
0					15.33		
0	60	13.33	8.0	5.33	20.67	0.00	0.00
$\boxed{12}$	75	50.00	24.0	26.00	$\boxed{46.67}$	0.00	3.00
12	75	16.67	26.0	-9.33	37.33	0.00	25.00
12	75	66.67	104.0	-37.33	0.00	0.00	5.00
0	66	14.67	10.0	4.67	4.67	0.00	0.00
0	60	26.67	16.0	10.67	15.33	0.00	0.00

The values shown in the boxes are selected as the optimal capacity of the battery and water tank

Table A-5a Freshwater-power storage cascade table (FWaPoSCT) for case study 3 (First operation day)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							First operation day							
Time-Interval Number (n)	Time (h)	Time Interval (h)	Sum Power rating (kW)	Sum electricity generation (kWh)	Delivered power to the RO (kW)	Electricity to battery (kWh)	Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)=initial value of water storage tank	Outsourced freshwater (m^3/h)
	0						0					0		
1	2	2	60	120	60	0	0	60	13	9.0	4.33	4.33	0.00	0.00
2	8	6	80	480	75	5	30	75	50	27.0	23.00	27.33	0.00	0.00
3	10	2	100	200	75	25	80	75	17	27.0	-10.33	17.00	0.00	0.00
4	18	8	80	640	75	5	120	75	67	108.0	-41.33	0.00	-24.33	-3.04
5	20	2	60	120	60	0	90	75	17	11.0	5.67	5.67	0.00	0.00
6	24	4	60	240	60	0	30	75	33	18.0	15.33	21.00	0.00	0.00

Table A-5b Freshwater-power storage cascade table (FWaPoSCT) for case study 3 (Normal operation day)

16	17	19	20	21	22	23
Normal operation day						
Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)
30					21.00	
0	75	16.67	9.0	7.67	28.67	0.00
30	75	50.00	27.0	23.00	$\boxed{51.67}$	0.00
80	75	16.67	27.0	-10.33	41.33	0.00
$\boxed{120}$	75	66.67	108.0	-41.33	0.00	0.00
90	75	16.67	11.0	5.67	5.67	0.00
30	75	33.33	18.0	15.33	21.00	0.00

The values shown in boxes are selected as optimal capacties of battery and water tank

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Table 1 Power sources for illustrative case studies 1 to 3

Power source	Time, (h)		Time interval, (h)	Power rating generated, (kW)			Electricity generation,(kWh)		
	From	To		Case 1	Case2	Case3	Case 1	Case2	Case3
Solar	**8**	**18**	**10**	**20**	**20**	**20**	**200**	**200**	**200**
Wind	**2**	**10**	**8**	**20**	**20**	**20**	**160**	**160**	**160**
Biomass	**0**	**24**	**24**	**60**	**60**	**60**	**1440**	**1440**	**1440**

Table 2 Freshwater demands for illustrative case studies 1 to 3

Freshwater demand appliances	Time, h		Time interval, h	Freshwater demand (m^3/h)		
	From	To		Case1	Case2	Case3
Consumer 1	**0**	**24**	**24**	**2**	**1**	**1.5**
Consumer 2	**8**	**18**	**10**	**4**	**5**	**5**
Consumer 3	**0**	**24**	**24**	**3**	**3**	**3**
Consumer 4	**8**	**18**	**10**	**3**	**3**	**3**
Consumer 5	**8**	**20**	**12**	**1**	**1**	**1**

Table 3 Freshwater storage cascade table (FWaSCT) for case study 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
										First operation day			Normal operation day		
Time-Interval Number (n)	Time (h)	Time Interval (h)	Sum Power rating (kW)	Sum electricity generation (kWh)	Delivered power to the RO (kW)	Wasted electricity (kWh)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m3)=initial value of water in tank	Outsourced freshwater (m^3/h)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)	Outsourced freshwater (m^3/h)
	0									0			8.00		
1		2	60	120	60	0.00	13	10.0	3.33	3.33	0.00	0.00	11.33	0.00	0.00
	2														
2		6	80	480	75	30.00	50	30.0	20.00	23.33	0.00	0.00	$\boxed{31.33}$	0.00	0.00
	8														
3		2	100	200	75	50.00	17	26.0	-9.33	14.00	0.00	0.00	22.00	0.00	0.00
	10														
4		8	80	640	75	40.00	67	104.0	-37.33	0.00	-23.33	-2.92	0.00	-15.33	-1.92
	18														
5		2	60	120	60	0.00	13	12.0	1.33	1.33	0.00	0.00	1.33	0.00	0.00
	20														
6		4	60	240	60	0.00	27	20.0	6.67	8.00	0.00	0.00	8.00	0.00	0.00
	24														

The value shown in box presented in column 14 is selected as the optimal volume of water storage tank

Table 4a Freshwater-power storage cascade table (FWaPoSCT) for case study 1 (First operation day)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
					First operation day									
Time-Interval Number (n)	Time (h)	Time-Interval duration (h)	Sum Power rating (kW)	Sum electricity generation (kWh)	Delivered power to the RO (kW)	Electricity to battery (kWh)	Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)=initial volume of water in tank	Outsourced freshwater (m^3/h)
	0						0					0		
1	2	2	60	120	60	0	0	60	13	10.0	3.33	3.33	0.00	0.00
2	8	6	80	480	75	30	30	75	50	30.0	20.00	23.33	0.00	0.00
3	10	2	100	200	75	50	80	75	17	26.0	-9.33	14.00	0.00	0.00
4	18	8	80	640	75	40	120	75	67	104.0	-37.33	0.00	-23.33	-2.92
5	20	2	60	120	60	0	90	75	17	12.0	4.67	4.67	0.00	0.00
6	24	4	60	240	60	0	30	75	33	20.0	13.33	18.00	0.00	0.00

Table 4b Freshwater-power storage cascade table (FWaPoSCT) for case study 1 (Normal operation day)

16	17	18	19	20	21	22	23
Normal operation day							
Electricity stored in battery (kWh)	Delivered power to the RO with battery (kW)	Fresh water production (m^3)	Total Fresh water demand (m^3)	Net freshwater Surplus/ deficit (m^3)	Volume of water in tank (m^3)	Outsourced freshwater (m^3)	Outsourced freshwater (m^3/h)
30					18.00		
0	75	16.67	10.0	6.67	24.67	0.00	0.00
30	75	50.00	30.0	20.00	$\boxed{44.67}$	0.00	0.00
80	75	16.67	26.0	-9.33	35.33	0.00	0.00
$\boxed{120}$	75	66.67	104.0	-37.33	0.00	-2.00	-0.25
90	75	16.67	12.0	4.67	4.67	0.00	0.00
30	75	33.33	20.0	13.33	18.00	0.00	0.00

The values shown in the boxes in columns 16 and 21 are selected as the optimal capacties of battery and water tank

Table 5 The outsourced freshwater, wasted power and storage sizes of the systems obtained by FWaPA and FWaPoPA

System configuration	**Operation day**	**RE-RO (base system)**			**RE-RO-WST**			**RE-RO-WSTB**		
Case study		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Integration method		**Direct coupling**			**FWaPA**			**FWaPoPA**		
Outsourced freshwater (m^3)	**First day**	**46.7**	**46.7**	**51.7**	**23.33**	**15.33**	**24.33**	**23.33**	**15.33**	**24.33**
	Normal day	**46.7**	**46.7**	**51.7**	**15.33**	**1.33**	**13.33**	**2**	**0**	**0**
Wasted power (kW)	**First day**	**101**	**137**	**119**	**35**	**35**	**35**	**33**	**0**	**0**
	Normal day	**101**	**137**	**119**	**35**	**35**	**35**	**33**	**0**	**0**

Water storage tank size (m^3)	**---**	**---**	**---**	**---**	**31.33**	**45.33**	**38.33**	**44.67**	**46.67**	**51.67**
Battery size (kWh)	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**120**	**12**	**120**

FIGURES

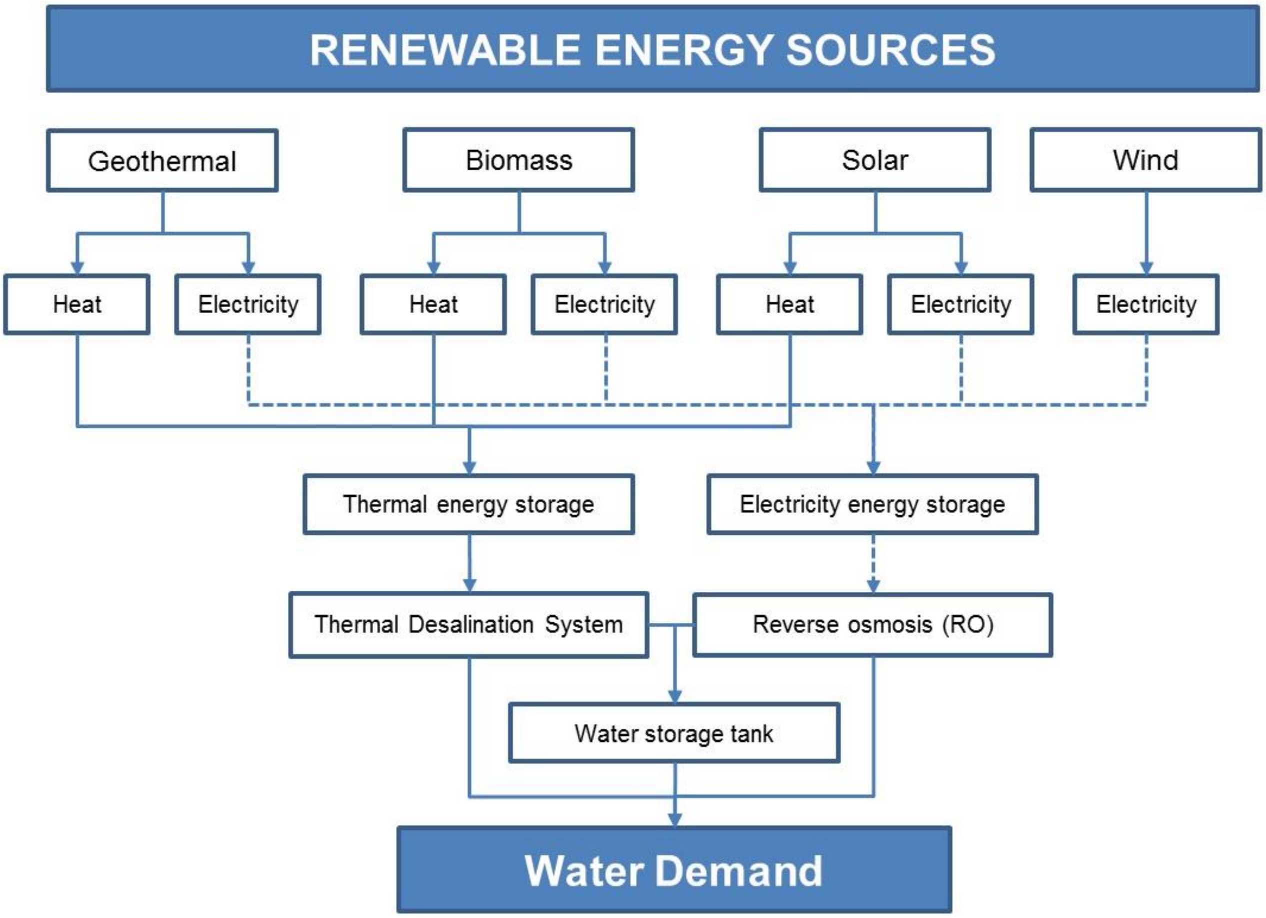
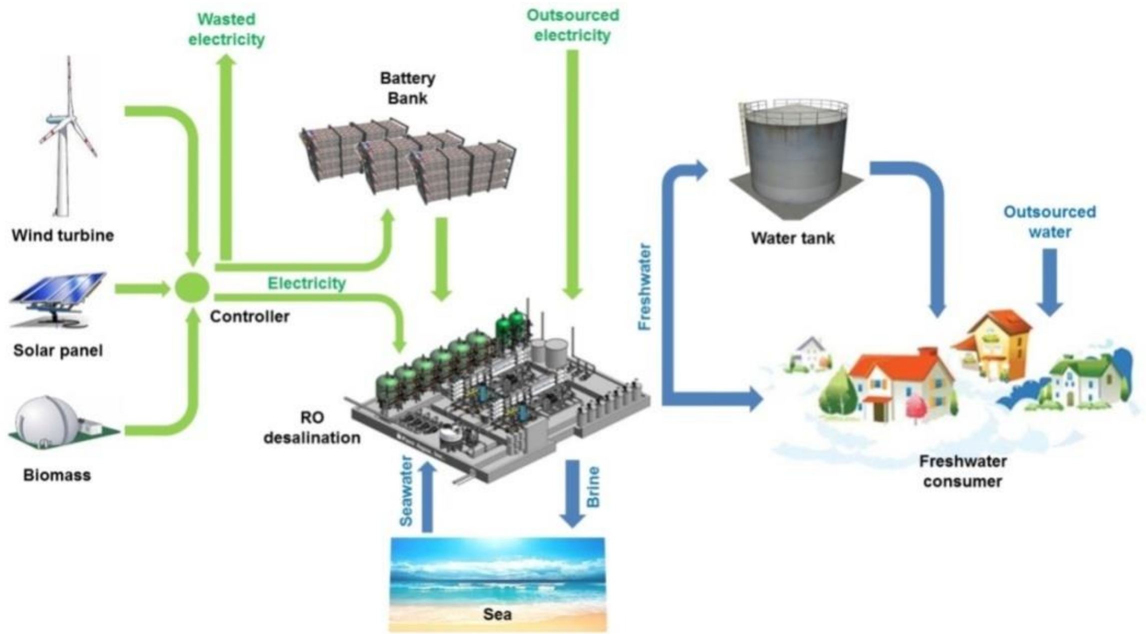
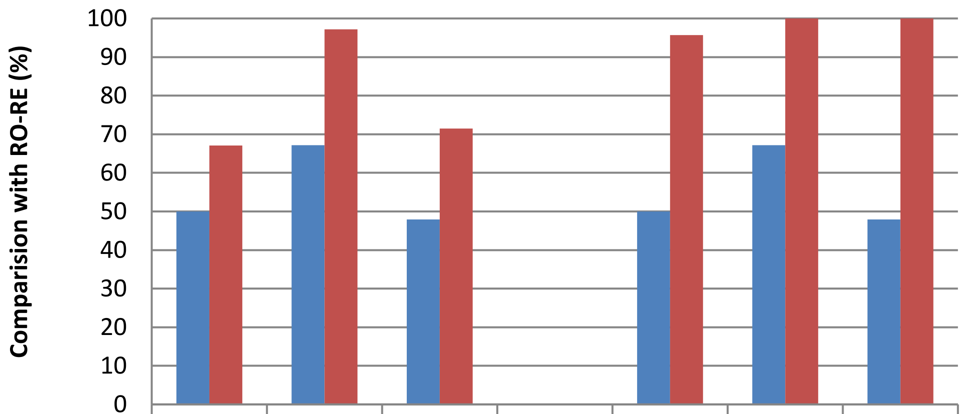


Fig. 1 The coupling of desalination systems with renewable energy sources and storage systems



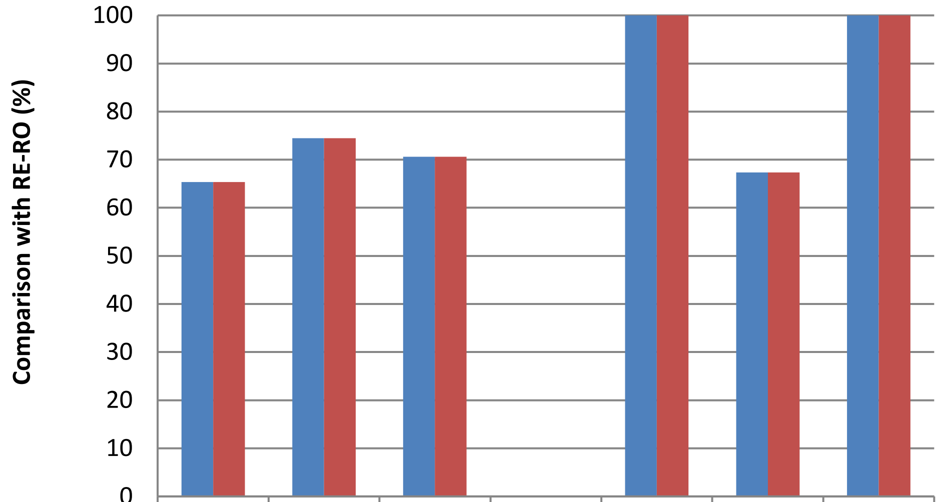
(c)

Fig. 2 Renewable energy-powered RO with water storage tank and battery (RE-RO-WSTB)



	case 1	case 2	case 3		case 1	case 2	case 3
First operation day	50/04	67/17	47/9		50/04	67/17	47/9
Normal operation day	67/1	97/15	71/45		95/71	100	100

Fig. 3 Comparison of the requirements for outsourced freshwater of RO-RE-WST and RO-RE-WSTB systems with the RO-RE system



	case 1	case 2	case 3		case 1	case 2	case 3
First operation day	65/34	74/45	70/59		100	67/32	100
Normal operation day	65/34	74/45	70/59		100	67/32	100

Fig. 4 Comparison of the wasted power of RO-RE-WST and RO-RE-WSTB systems with the RO-RE system