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Optimization coupling RO desalination unit to renewable energy by genetic algorithms

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ABSTRACT

Renewable energy sources (RES) for powering desalination processes is a promising option especially in remote and arid regions where the use of conventional energy is costly or unavailable. Reverse osmosis (RO) is one of the most suitable desalination processes to be coupled with different RES such as solar and wind. If RES/RO systems are optimally designed, some combinations can be cost effective and reliable. However, the design of such systems is complex because of uncertain renewable energy supplies, load demands, and the non-linear characteristics of some components. In such system, different scenarios can be suggested; i.e. combinations of Photovoltaic (PV) panels, type and number of batteries, type and number of turbines, etc. Therefore, it is difficult to determine the optimal configuration with classical techniques. The development of a tool to integrate all parameters involved and compare between the possible scenarios is very important. This paper presents a new model based on the genetic algorithms allowing for coupling small RO unit to RES. A particular interest is focused on the hybrid systems (PV/WIND/Batteries/RO). The objective function to minimize corresponds to the total water cost (capital cost plus operational costs). The feasible solutions (individuals in each generation) are obtained through simulations carried along a complete year.

Keywords: Desalination; Reverse osmosis; Renewable energies; Modeling; Genetic algorithms; Optimization

1. Introduction

The application of renewable energies (RE) for driving desalination units (DES) is very promising in isolated areas (i.e. islands, villages in the desert, etc.), where the electricity production is very expensive, potable water resources are inexistent and the potential of RE (solar and wind) is very important [1,2]. The application of RE in the desalination industry does not face the same barriers as in the case of renewable energy source (RES) for electricity power production (expensive storage systems to compensate the stochastic characteristics of the RE). In the case of RES/DES coupling, the energy is consumed directly for water production, the water can be stored, cheaply in large quantities and for long periods [1].

The operational performances, the cost and the reliability of RES/DES units depend on the design and calibration of such systems. Optimal use of RES potential is necessary in order to reduce the cost of

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produced water. In this frame, considering hybrid configurations (Photovoltaic (PV) and Wind) is the best way to optimize the use of RE.

On the other hand, the design of such systems is complex because of uncertain RE supplies, load demands, and the non-linear characteristics of some components.

Despite the great effort done to improve the efficiency of RES/DES systems the desalinated water cost is still relatively high compared to conventional desalination units and more effort should be done to optimize this kind of systems.

In this paper we present different methods to optimize RE systems driving desalination unit, with a particular interest to the reverse osmosis (RO) driven by hybrid PV/Wind systems. For this last configuration we will present a new methodology based on genetic algorithms (GAs).

The objective function used in this optimization is the unit cost of desalinated water during the life cycle of the plant (20 years). The presented methodology consists in selecting from available components in the market, the optimal number and the type of each unit (PV panels, wind turbines, membranes, etc.) in such way that the water needs are satisfied and the production cost is minimized. The total water cost for the life cycle of the plant is equal to the sum of the capital and maintenance costs.

The present methodology has the advantage to take into account all the critical functioning parameters that have an influence on the electricity and desalinated water productions and the investment and operational costs.

The minimization of the function total cost was implemented by using GAs that have the capacity to reach the solution corresponding to the global optimum with a relative simple calculation. The benefit of using GA in the proposed methodology is the calculation of the optimal solution in the global space of feasible solutions of desalination systems (individuals). These later are obtained by different simulations throughout a year.

2. RE/DES Systems

Many different RE desalination systems are technically feasible [2–4]. Fig. 1 presents the possible combinations between desalination processes and RE technologies.

A methodology for selecting the most appropriate combination between desalination technologies and RE for a given site based on different criteria was developed [5]. Desalination systems are energy intensive, and their energy consumption is a driving factor in determining their economic feasibility when they are coupled to RES. Typical energy consumptions for different desalination processes are shown in Table 1.

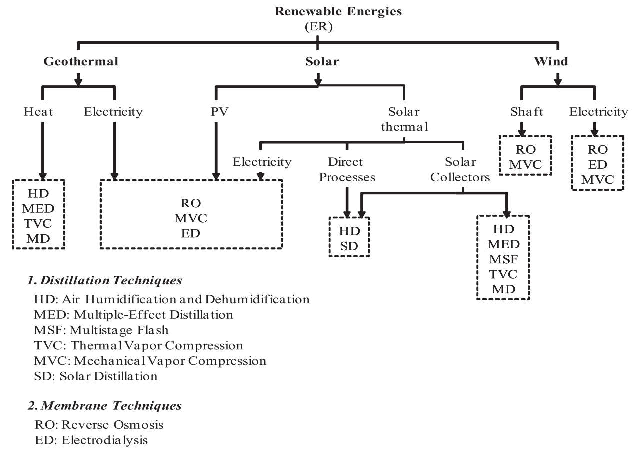

Fig. 1. Technological combinations of the main RE and desalination methods.

Table 1
Energy consumption and electric power cogeneration [6]

Desalination process	Thermal energy (kJ/kg)	Electrical energy (kWh/m^3)
Seawater		
MSF	190–290	4–6
MED	150–290	2.5–3
Vapor compression (VC)	–	8–12
RO without energy recovery	–	7–10
RO with energy recovery	–	3–5
Brackish water		
RO without energy recovery		1–3
RO with energy recovery		1.5–4
Electrodialysis		1.5–4

In Table 1 the energy requirements are separated into thermal energy which is used to heat the seawater and electrical energy which is used to drive pumps, compressors, and auxiliary equipment. For seawater desalination, RO requires the least amount of overall energy. However, if thermal energy is inexpensive (the case of Middle East), a thermal desalination process like multi-effect distillation can be practical.

Fig. 2 illustrates the breakdown of RE-powered desalination system technologies implemented worldwide in 2007 [7]. It shows that the most used

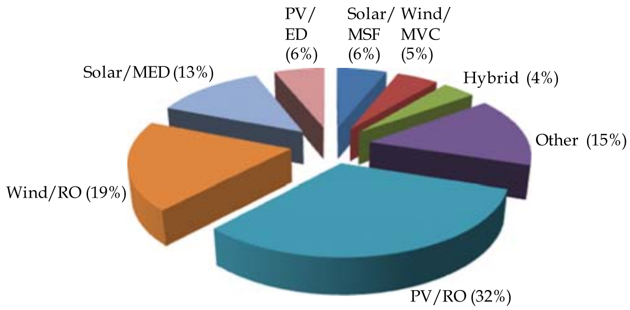

Fig. 2. Breakdown of RE powered desalination system technologies implemented worldwide [7].

RES/Desalination systems are RES/RO (51% of the total worldwide installed RES/DES plants).

RO is the desalination process which can be coupled, in reliable and economic way, with RES. The suitability of RE technologies, especially wind turbines and PVs, for RO desalination systems is due to the convenience of RO for desalinating small quantity of water for remote and isolated areas; it has low energy consumption (Table 1) and little need for maintenance [8].

2.1. MSF desalination plants driven by solar energy

Solar-powered multi-stage flash (MSF) plants can produce 6–60 L/m^2/day, in comparison with the 3–4 L/m^2/day typical of solar stills [9].

The use of solar troughs for MSF desalination was tested mainly in the USA. In a typical commercial small plant 48 kW is required to produce 450 L/day in three stages.

In Szacsvay et al. [10], a Solar/MSF system using an Atlantis autoflash multistage desalination unit is described. Since the standard MSF process is not able to operate coupled to any variable heat source, an adapted MSF system called "Autoflash" was developed. Performance and layout data were obtained both from computer simulation and experimental results with a small-sized Solar/MSF systems in Switzerland. The system had been in operation for 9 years. From these studies it was shown that the cost of distillate could be reduced from 5.48$/m^3 for small desalination system with a capacity of 15 m^3/day to 2.39$/m^3 for desalination systems with a capacity of 300 m^3/day.

2.2. Multiple-effect distillation driven by solar energy

Several multiple-effect distillation (MED) plants of medium capacity powered by solar energy were built worldwide. One MED-plant designed for a maximum capacity of 120 m^3/day with 18 stack-type stages and pre-heaters was analyzed in UAE [11]. Evacuated-tube solar collectors of 1,862 m^2 were used with water as the heat-carrying medium. It had a heat accumulator of 300 m^3 capacity. Specific heat consumption of the plant was 43.8 kcal/kg with performance ratio of 12.4. Due to heat accumulator the evaporator could run 24 h a day during sunny days producing freshwater of 85 m^3/day. The plant was able to desalt seawater of 55,000 ppm. The total seawater requirement was 42.5 m^3/h. The major problem was the maintenance of the pumps. It was shown that the acid cleaning and silt removal were extremely necessary for better performance of the plant.

A practical-scale desalination system of three effects using only solar energy from solar collectors as the heat source and the electrical power from the PV-cells was investigated by Abu-Jabal et al. [12]. The unit was developed and manufactured by the Ebara Corporation (Tokyo) and tested at the Al Azhar University in Gaza. The average production rate was in the range 6–13 L/m^2/day.

Thomas [13] carried several experiments on MED and MSF units driven by solar energy in Kuwait. He reported several difficulties operating under the variable conditions of solar insulation. Greater success has been found with self-regulating solar MSF plants than solar MED plants.

Fiorenza et al. [14] estimated the produced water cost for seawater desalination by MED powered by a solar thermal field. The results obtained for plants of capacity varying between 500 and 5,000 m^3/d have shown that the cost of water produced can be reduced by increasing the plant capacity; i.e. 3.2$/m^3 for the 500 m^3/d plant capacity and 2$/m^3 for the 5,000 m^3/d plant capacity.

2.3. RO desalination driven by PV

PV-powered RO systems have been implemented in different regions, i.e. remote areas of the Tunisian desert, rural areas of Jordan, remote communities in Australia, etc. Several investigations were carried to analyze the cost of PV/RO desalination systems [15]. If PV connected to a RO system is commercial nowadays, the main problem of this technology is reported to be the high cost of the PV cells. The distance at which the PV energy is competitive with conventional energy depends on the plant capacity, on the distance to the electric grid, and on the salt concentration of the feed [16].

In Saudi Arabia, a PV/RO brackish water desalination plant was installed [17]. It was connected to a solar still with 5 m^3/d production. The feed water of the water still was the blowdown of the RO unit ($10\,m^3$/d). A detailed cost analysis was also reported.

Bourouni and Chaibi [18] presented a PV/RO desalination plant, for supplying one village, in southern Tunisia. It uses solar energy to power a RO brackish water desalination unit with a capacity of $15\,m^3$/day. They present an analytical description of the plant components and reports experimental results for a 6-month operating period. Several problems were highlighted such as brine rejection, low efficiencies, and high cost.

Several tools were developed to improve the design of PV/RO systems by using iterative procedure [19]. The size of the RO unit is computed according to the desalinated-water requirements, while the PV system nominal power rating is calculated such that the corresponding energy requirements of the RO unit are satisfied, taking into account the available solar radiation potential of the installation area. The size of the battery incorporated in the system is computed such that the daily variations of the solar radiation are compensated. On the other hand, up to now the design process does not include the optimization of the components' number and type and the minimization of the total system cost.

2.4. RO driven by wind energy

Since the coastal areas present a high availability of wind power resources, wind-powered desalination represents a promising alternative of RE desalination [20]. Wind-powered RO plants have been implemented on the islands of the County of Split and Dalmatia (Croatia), on the island Utsira in Norway, and in remote communities in Australia.

A prototype wind-powered RO desalination system was constructed and tested on Coconut Island off the northern coast of Oahu, Hawaii, for brackish water desalination [21]. The system has four major subsystems: multivaned windmill/pump, flow/pressure stabilizer, RO module, and control mechanism. It was shown that the flow rate of 13 l/min could be processed for an average wind speed of 5 m/s, and a brackish feed water at a total dissolved solids concentration of 3,000 mg/l. The average rejection rate and recovery ratio were 97 and 20%, respectively. Energy efficiency equal to 35% was shown to be comparable to the typical energy efficiency of well-operated multivaned windmills.

A prototype of a fully autonomous wind-powered desalination system has been installed on the island of Gran Canaria in the Canarian Archipelago [22]. The system consists of a wind farm, made up of two wind turbines and a flywheel, which supplies the energy needs of a group of eight RO modules throughout the complete desalination process (from the pumping of seawater to the storage of the product water), as well as the energy requirements of the control subsystems. It was highlighted that this system can be applied to seawater desalination, both on a small and large scale, in coastal regions with a scarcity of water for domestic and/or agricultural use.

The economic feasibility of a wind-powered RO plant was evaluated by mathematical modeling analysis [7]. It was shown that the costs of a wind-powered RO desalination system are in line with what is expected for a conventional desalination system, proving to be particularly cost-competitive in areas with good wind resources that have high costs of energy. The unit cost of freshwater production by a conventional RO plant can be reduced up to 20% for regions with an average wind speed of 5 m/s or higher.

In order to optimize the design of Wind/RO systems, Kiranoudis et al. [20] considered desalination plants power-supplied by one wind generator (W/G). The optimal design objectives are the determination of the optimum size and type of the W/G and the optimum structure of the RO desalination unit membranes, such that the system total annual cost is minimized, with respect to certain product quality and quantity demand constraints. This procedure is implemented using a successive quadratic optimization algorithm. The W/G-desalination systems investigated do not incorporate either electric energy, or produced water storage units.

2.5. RO desalination driven by hybrid PV/wind systems

RO desalination units driven by hybrid PV/wind power systems have been designed and implemented in different areas of the world (e.g. Sultanate of Oman, Israel, Mexico, Tunisia, etc.). The performances of these units were reported by Weiner et al. [8], Peterson et al. [23], Bourouni and Chaibi [8] and Peterson et al. [24].

Two RO desalination plants (Germany) using a plate module system supplied by a 6-kW wind energy converter and a 2.5 kW solar generator have been designed for remote areas (Peterson et al. [24]). Two of these prototypes were installed in the northern part of Mexico and in a small island on the German coast of the North Sea (Peterson et al. [23]).

The design of a stand-alone, hybrid PV/Wind system, used to power-supply a seawater RO desalination unit, based on a technoeconomic analysis, is proposed by Mohamed and Papadakis [25]. The system contains both a battery bank and a storage tank for the produced water, in order to cover the potable water demand during the days with negligible solar and/or wind energy production. The RO unit is designed to be able to cover the maximum daily water demand, dictating the corresponding maximum total power requirements. In the second step of the proposed methodology, the number of PV modules is calculated such that the maximum energy requirements during the year are covered, taking into account the available solar radiation potential. The battery bank capacity is computed such that the electric energy required for two days can be stored. The volume of the water storage tank is calculated in such way that it provides two summer-day autonomy. In order to minimize the total system cost, the developed software eliminates a part of the PV modules, determines the corresponding produced daily energy and replaces them by one or more W/G. This calculation is performed for various combinations of PV and W/G contribution percentages to the hybrid system total energy production. The combination achieving the minimum water production cost is selected as the final hybrid system configuration.

Manolakos et al. [26] discussed the developement and the application of a software tool for designing hybrid PV/Wind systems, which are used to cover the electricity and water demands of remote areas. The nominal power rating of the W/G and the number of the PV modules are determined through several program runs simulating the system operation, in order to satisfy the electric energy and water needs. The battery bank is sized taking into account several days of energy autonomy of the system, in order to ensure the uninterrupted power supply during the time periods of low solar radiation and/or low wind speed. The volume of the desalinated water tank is computed to satisfy the water demand, even during the time periods of low RES potential availability.

Voivontas et al. [27] developed a computer-aided design tool for the preliminary design of desalination plants driven by RES and the evaluation of the corresponding water production cost. The RES power production capability is determined using an iterative procedure allowing an energy balance between the energy produced by the RES and the auxiliary energy sources (e.g. electric grid, diesel generators, etc.) and the energy requirements of the desalination unit. However, this design method does not include the economic optimization of the resulting configurations. The investigations carried on RO desalination plants driven by hybrid PV/Wind systems showed that this kind of units is the most efficient compared to the other RES/DES technologies. Moreover, this technology can be improved by optimizing the design of the overall plant. For these reasons we focus in this chapter on the optimization of this kind of systems.

3. New methodology of optimization hybrid PV/WIND/RO systems

The operational performance and the reliability of the desalination systems driven by RES depend on their proper design and sizing. The optimal exploitation of the available RES potential is necessary in order to reduce the cost of the water produced.

The objective of this paper is to present a new methodology to optimize RO desalination system, which is power-supplied by hybrid PV and W/G energy sources. Compared to the past-proposed methodologies, which have been used in order to design water desalination systems driven by RES, the methodology presented in this paper has the advantage to take into account all the critical operational parameters that affect both the resulting electric energy and desalinated-water production levels and the system capital and maintenance costs. The block diagram of the PV/Wind/RO system considered in this study is illustrated in Fig. 3.

The Battery bank is charged from the respective PV and W/G input power sources by using battery chargers, connected to a common DC bus. The power sources are usually configured in multiple power generation blocks according to the devices nominal power ratings and the redundancy requirements. The battery bank, which is usually of lead-acid type, is used to store the generated electric energy surplus and to supply the RO desalination units in case of low solar radiation and/or wind speed conditions. DC/AC converters are used to interface the DC battery voltage to the AC requirements of the RO desalination units. A water tank is used to store the produced desalinated water surplus, which is not directly consumed.

The purpose of the proposed methodology is to derive, among a list of commercially available system devices, the optimal number and type of units such that the life time round total system cost (CO_{Tot}) is

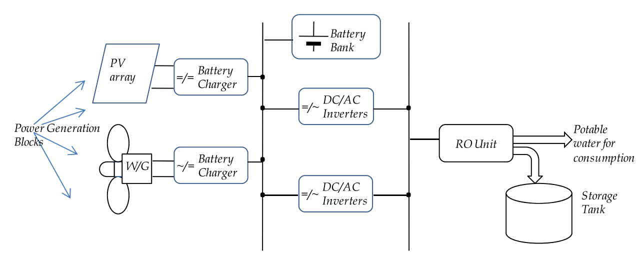

Fig. 3. Block diagram of RO driven by Hybrid PV and W/G energy sources.

minimized. At the same time the desalinated-water demand is completely covered.

CO_{Tot} is equal to the sum of the respective components' capital and maintenance costs. The decision variables for the optimization are: (i) the number and the type of the membranes, (ii) the number and the type of the PV modules, (iii) the number and the type of the wind turbines, (iv) the batteries charger, (v) the DC/AC converters, (vi) the height of the turbines, and the volume of the storage tank.

The minimization of the system total cost function has been implemented using GAs, which have the ability to attain the global optimum solution with relative computational simplicity. The scope of the GAs in the proposed methodology is the calculation of the optimum solutions in the overall state space of the desalination system-sizing problem.

The block diagram depicted in Fig. 4 summarizes the proposed optimization methodology. This methodology uses a database including: (i) the technical characteristics of commercially available system devices, (ii) their associated per unit capital, and (iii) their maintenance costs. The input of the model are the: (i) feed and the desalinated water quality specifications, (ii) water demand profile, (iii) daily solar irradiation on a horizontal plane, and (iv) the hourly mean values of ambient temperature and wind speed.

At the first step, the RO plant is designed and optimized based on water demand, feed water characteristics, and desalinated water specifications. One important outcome of this step is the determination of

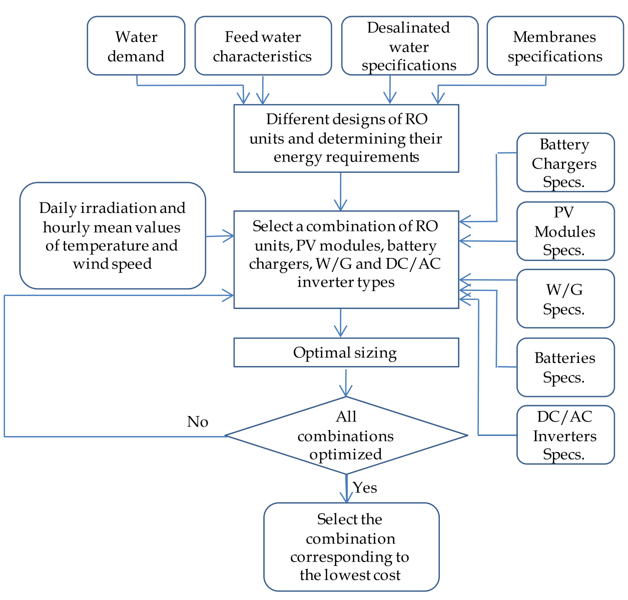

Fig. 4. The flowchart of the proposed optimization methodology.

the energy required to operate the pumps and other auxiliaries. In the second step, special attention is paid to the design of energy systems related to the chosen technology and the arrangements of various components that can meet the goal of energy demand. In this step, the structure of the power unit, batteries, water storage, and inverters are studied. Several Hybrid PV/Wind combinations are possible to power the designed RO plant. To validate the RES configuration, a simulation of the system operation is performed during the year in order to examine whether it fulfils the desalinated-water requirements.

In the third step, a process employing GAs is executed, in order to dynamically search for the system configuration, which subject to the criterion set in the first step, results in minimum total system cost.

During the application of the proposed methodology, the system operation is simulated for one year with a time step of 1 h. The power produced by the PV and W/G sources and the desalinated-water flow rate are assumed to be constant during that time step and they are arithmetically equal to the corresponding energy and water volume, respectively.

3.1. Modeling of the RO unit

The equations of flow and salt distribution, used in the model, are similar to those provided by the software for the design of RO membrane "FILMTEC-ROSA" [28].

RO membranes are selected after checking the feed water characteristics. Hence, the number of membranes N_{mb} which is a function of unit capacity, the stream flow Q_p, and the membrane surface S_{mb} is calculated as follows:

$$N_{mb} = \frac{Q_p}{f \cdot S_{mb}} \tag{1}$$

where f is the pure water transport coefficient.

The number N_{tp} of pressure vessels in the system is calculated the following equation:

$$N_{tp} = \frac{N_{mb}}{N_T} \tag{2}$$

where N_T is the total number of membranes per unit.

Eq. (3) is used to calculate the water flow rate produced by RO membranes.

$$Q_p = A \cdot S_{mb} \cdot \text{TCF} \cdot F \cdot (\Delta P - \Delta \Pi) \tag{3}$$

A is the membrane pure water permeability, TCF is the temperature correction factor, F is the membrane fouling factor ($0.8 \leq F \leq 1$), ΔP is the applied transmembrane pressure and $\Delta\pi$ is the transmembrane osmotic pressure.

The osmotic pressure in the different elements of RO unit is given by Eq. (4).

$$\pi = 0.002654 \cdot (T + 273) \cdot C \cdot \frac{1}{1,000 - \frac{C}{1,000}} \tag{4}$$

where C is the salt concentration.

The average pressure drop ΔP between the first and the last element is given by Eq. (5).

$$\Delta P = P_{\mathrm{f}} - 1/2\Delta P_{\mathrm{fs}} \tag{5}$$

ΔP_{fs} represents the pressure drop between feed and discharge of a single element, it is given as follows:

$$\Delta P_{\mathrm{fs}} = 0.01 \cdot \overline{Q}_{\mathrm{fc}}^{1.7} \tag{6}$$

The efficiency (Y_{k}) of the membrane is a function of the overall performance of the RO system Y and N_{mb} in the system Eq. (7).

$$Y_k = 1 - (1 - Y)^{1/N_{\mathrm{mb}}} \tag{7}$$

The product concentration C_{P} is a function of recovery rate and salt rejection (Eq. (8)). The brine concentration C_{c} of RO element is calculated from Eq. (9).

$$C_{\mathrm{p}} = (1 - R_{\mathrm{mb}}) \times C_{\mathrm{fc}} \times p_{\mathrm{f}} \times \mathrm{TCF} \times \frac{S_{\mathrm{mb}}}{Q_{\mathrm{p}}} \tag{8}$$

$$Q_{\mathrm{f}} \cdot C_{\mathrm{f}} = Q_{\mathrm{p}} \cdot C_{\mathrm{p}} + Q_{\mathrm{c}} \cdot C_{\mathrm{c}} \tag{9}$$

By applying Eqs. (6–8) the: flow rates and concentrations of permeate and concentrated brine in the first element are determined respectively. Thus, product water is collected in the central tube and the brine becomes feed to the second element. This process is repeated for all elements in series. To determine the feed pressure of the system, the model starts from last element for which the applied pressure P_{a} is calculated from Eq. (3).

The total water quantity Q_{T} produced by RO system is given by Eq. (10). Where Q_{k} is the amount of water produced by the cell k. The desalinated water salinity concentration is deduced from Eq. (11).

$$Q_{\mathrm{T}} = \sum_{k=1}^{N_{\mathrm{mb}}} Q_{\mathrm{k}} \tag{10}$$

$$C_{\mathrm{T}} = \frac{\sum_{k=1}^{N_{\mathrm{mb}}} C_k \cdot Q_k}{Q_{\mathrm{T}}} \tag{11}$$

It should be noted that many other parameters are considered in the model including estimation of the water needs, chemical analysis of the feed water, and the choice of the membranes. The optimal system design is targeting towards the minimization of the RO energy consumption. In this frame, energy recovery systems can be considered.

3.2. Modeling of the PV panels

Each PV power generation block shown in Fig. 3, consists of N_{P} PV modules connected in parallel and N_{S} PV modules connected in series. On day i ($1 \leq i \leq 365$) and at hour t ($1 \leq t \leq 24$) the maximum output power of each PV power generation block is determined. This calculation is based on the specifications of the PV module under Standard Test Conditions (STC, cell temperature = 25℃ and solar irradiance = 1 kW/m^2), provided by the manufacturer, as well as the ambient temperature and solar irradiation conditions. The following Eqs. (12–15) are used to design the PV modules:

$$P_{\mathrm{M}}^i(t) = N_{\mathrm{s}} \cdot N_{\mathrm{p}} \cdot V_{\mathrm{OC}}^i(t) \cdot I_{\mathrm{SC}}^i(t,\beta) \cdot \mathrm{FF}^i(t) \tag{12}$$

$$I_{\mathrm{SC}}^i(t,\beta) = \{I_{\mathrm{SC,STC}} + K_{\mathrm{I}}[T_{\mathrm{c}}^i(t) - 25^\circ C]\} \cdot \frac{G^i(t,\beta)}{1,000} \tag{13}$$

$$V_{\mathrm{OC}}^i(t) = V_{\mathrm{OC,STC}} - K_{\mathrm{v}}[T_{\mathrm{c}}^i(t) - 25^\circ C] \tag{14}$$

$$T_{\mathrm{c}}^i(t) = T_{\mathrm{A}}^i(t) + \frac{\mathrm{NOCT} - 20^\circ C}{800} \cdot G^i(t,\beta) \tag{15}$$

where $P_{\mathrm{M}}^i(t)$ is the maximum output power of the PV array, $I_{\mathrm{SC}}^i(t,\beta)$ is the PV module short-circuit current (A), $I_{\mathrm{SC,STC}}$ is the short-circuit current under STC, $G^i(t,\beta)$ is the global irradiance (W/m^2) incident on the PV module placed at tilt angle β (°), K_{I} is the short-circuit current temperature coefficient (A/℃), $V_{\mathrm{OC}}^i(t)$ is the open-circuit voltage (V), $V_{\mathrm{OC,STC}}$ is the open-circuit voltage under STC (V), K_{v} is the open-circuit voltage temperature coefficient (V/℃), $T_{\mathrm{A}}^i(t)$ is the ambient temperature (℃), NOCT is the Nominal Operating Cell Temperature (℃), provided by the manufacturer and $\mathrm{FF}^i(t)$ is the Fill Factor, [29].

The number of PV modules connected in series in each PV power generation block, N_{s}, is calculated according to the battery charger maximum input voltage, V^m_{DC}, and the PV modules maximum open-circuit voltage level, V^m_{OC}:

$$N_s = \frac{V^m_{\mathrm{DC}}}{V^m_{\mathrm{OC}}} \tag{16}$$

The values of the daily solar irradiation on the horizontal plane are used to calculate the value of $G^i(t,\beta)$ according to the methodology analyzed by Lorenzo [30].

The battery charger power conversion factor n_s is defined as follows:

$$n_s = \frac{P^i_{\mathrm{PV}}(t,\beta)}{P^i_{\mathrm{M}}(t,\beta)} = n_1 \cdot n_2 \tag{17}$$

where $P^i_{\mathrm{PV}}(t,\beta)$ is the PV power really transferred to the battery bank by each PV power generation block, n_1 is the battery charger power electronic interface efficiency and n_2 is a conversion factor, which depends on the battery charging algorithm executed during the charger operation and indicates the deviation of the actual PV power generated from the corresponding maximum power.

In case that the battery charger operates according to the maximum power point tracking (MPPT) principle [31], n_2 is approximately equal to 1, otherwise its value is much lower. The values of n_1 and n_2 are specified by the battery charger manufacturer.

3.3. Modeling of W/G

The variation of the W/G output power vs. the wind speed is provided by the manufacturer. It usually indicates the actual power transferred to the battery bank from the W/G source, taking into account the effects of both the battery charger power electronic interface efficiency and the MPPT operation, if available. Thus, in the proposed methodology, the power transferred to the battery bank at hour t of day i, from each W/G power generation block, $P^i_{\mathrm{WG}}(t,h)$, is calculated using the following linear relation:

$$P^i_{\mathrm{WG}}(t,h) = P_1 + \left[v^i(t,h) - v_1\right] \cdot \frac{P_2 - P_1}{v_2 - v_1} \tag{18}$$

where h (m) is the W/G installation height, $v^i(t,h)$ is the wind speed (m/s) at height h ($h_{\mathrm{low}} \leqslant h \leqslant h_{\mathrm{high}}$ according to the limits h_{low} and h_{high} specified by the W/G manufacturer), and (P_1, v_1), (P_2, v_2) are the W/G output power and wind speed pairs.

If the input wind speed data are measured at a different height than the desired W/G installation height, h, then, $v^i(t,h)$ is corrected using the following exponential law:

$$v^i(t,h) = v^i_{ref}(t) \cdot \left(\frac{h}{h_{\mathrm{ref}}}\right)^{\alpha} \tag{19}$$

where $v^i_{ref}(t)$ is the reference (input) wind speed (m/s) measured at height h_{ref} (m) and the exponent α ranges from 1/7 to 1/4.

3.4. Modeling of batteries

The number of batteries connected in series in each of the multiple, parallel-connected battery strings forming the battery bank, n^s_B, depends on the nominal DC bus voltage and the nominal voltage of each individual battery, V_B (V):

$$n^s_{\mathrm{B}} = \frac{V_{\mathrm{BUS}}}{V_{\mathrm{B}}} \tag{20}$$

The value of the battery bank nominal capacity, C_n (Ah), depends on the total number of batteries, N_{BAT}, the number of series connected batteries, and the nominal capacity of each battery, C_{B} (Ah):

$$C_n = \frac{N_{\mathrm{BAT}}}{n^S_{\mathrm{B}}} \cdot C_{\mathrm{B}} \tag{21}$$

The maximum permissible battery depth of discharge, DOD (%) is specified by the system designer at the beginning of the optimal sizing procedure and it dictates the value of the minimum permissible battery bank capacity during discharging, $C_{\min}$ (Ah), which is calculated as follows:

$$C_{\min} = \mathrm{DOD} \cdot C_n \tag{22}$$

During the desalination system operation the available battery bank capacity is modified according to the PV and W/G energy production levels and the power requirements of the desalination units. This variation is expressed by the following equation:

$$C^i(t) = C^i(t-1) + n_{\mathrm{B}} \cdot \frac{P^i_{\mathrm{B}}(t)}{V_{\mathrm{BUS}}} \cdot \Delta t \tag{23}$$

$$C^i(24) = C^{i+1}(0) \tag{24}$$

where C_i (t) and C_i $(t-1)$ are the available battery capacity (Ah) at hour **t** and $t-1$, respectively, of day i, $n_{\mathrm{B}} = 80\%$ is the battery round-trip efficiency during charging and $n_{\mathrm{B}} = 100\%$ during discharging [32], V_{BUS}

is the nominal DC bus voltage (V), $P^i_B(t)$ is the battery input/output power (W) ($P^i_B(t)<0$ during discharging and $P^i_B(t)>0$ during charging) and Δt is the simulation time step ($\Delta t = 1$ h).

In order to avoid the battery performance degradation under practical operating conditions the maximum permissible battery bank charging or discharging current has been limited to ($C_n/5$) h. The initial capacity of the battery bank, C_1 (0), is calculated using the following equation:

$$C^1(0) = (\frac{1 - \mathrm{DOD}}{2}) \cdot C_n \tag{25}$$

3.5. Modeling of the global RE/DES system

The PV panels and W/G must be sized such that the produced energy during the year allows to completely satisfy the desalination system energy requirements. Hence, the remaining battery bank capacity at the end of the simulation period must be higher than its initial value:

$$C^{365}(24) \geq C^1(0) \tag{26}$$

When the necessary power for the RO operation is available, then the desalination process is performed and desalinated water is produced. Otherwise, the operation of the RO units is suspended. In this case, cleaning of each RO unit membranes should be performed, using flushing techniques. The total power produced by the PV and Wind Turbines at hour t of day i is calculated as follows:

$$P^i_{RE}(t) = N^{PV}_{ch} \cdot n_S \cdot P^i_M(t, \beta) + N_{WG} \cdot P^i_{WG}(t, h) \tag{27}$$

where N_{WG} is the total number of W/G power generation blocks incorporated in the desalination system. At the hour t of the day i the total DC power input to the DC/AC inverters, $P^i_T(t)$ (W), is related with the total AC power supplying the desalination units, $P^i_{RO}(t)$ (W), according to the following equation:

$$P^i_T(t) = \frac{P^i_{RO}(t)}{n_i} \tag{28}$$

where n_i (%) is the power conversion efficiency of the DC/AC inverters. The minimum permissible amount of water stored in the tank, V_{min} (m^3), should be fixed (generally set equal to 25–30% of the tank total volume, V_{TANK} (m^3)).

The volume of the available water stored in the tank at hour t of day i, $V^i(t)$ (m^3), is modified during the desalination system operation, such that:

$$V_{min} \leq V^i(t) \leq V_{TANK} \tag{29}$$

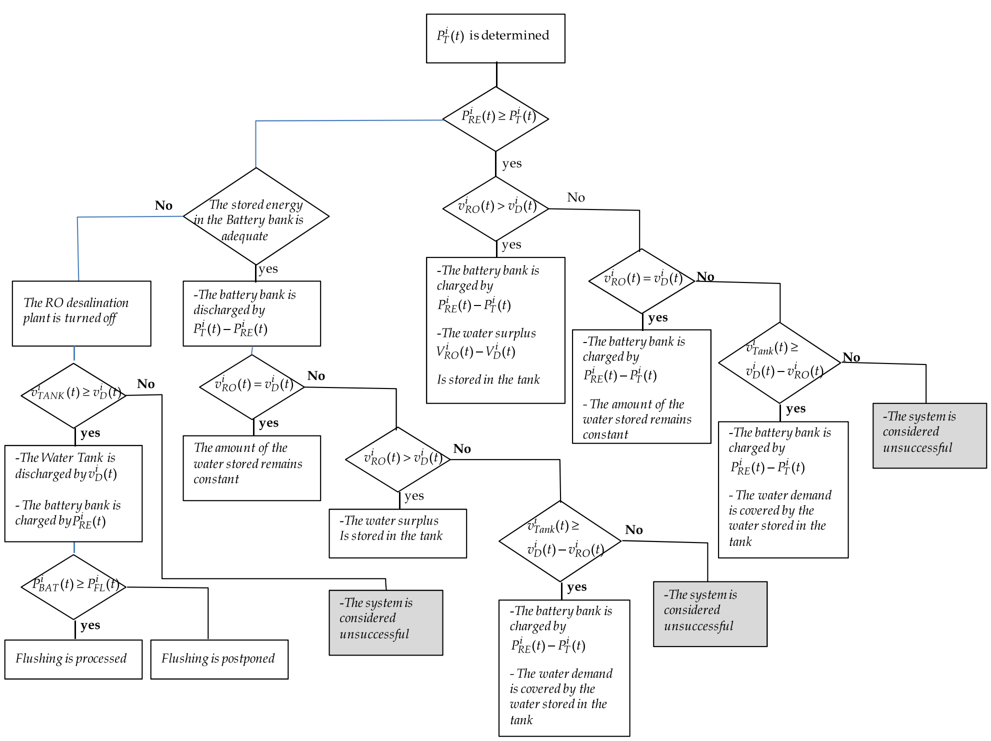

Fig. 5. The flowchart of energy and water flows among the components of the system.

When the desalinated water demand at hour t of day i $V_D^i(t)$, (m^3), is defined then the energy and water flows among the components of the system can be described by Fig. 5.

The developed desalination system model should be used to simulate the system operation on a yearly basis to check the feasibility of the proposed solution. The optimization of the whole system is achieved by using the GA methods by considering potential solutions.

3.6. System total cost minimization using GAs

The GAs are used for designing and sizing a, through the calculation of optimum solutions in the overall state space. The role of the GA is to derive the optimal desalination system configuration by selecting chromosomes from the total state space of potential solutions, which minimize the problem's objective function and simultaneously lead to a successful system operation during the whole year.

GAs is an optimum search technique based on the concepts of natural selection and survival of the fittest individuals.

It works with a fixed-size population of possible solutions of a problem, which are evolving in time. A GA utilizes three principal genetic operators; selection, crossover and mutation. Compared to conventional optimization methods, such as dynamic programming and gradient techniques, GAs are able to: (i) handle complex problems with linear or non-linear cost functions, both accurately and efficiently and (ii) attain the global optimum solution with relative computational simplicity, without being restricted by local optima [33].

The GA chromosomes are in the form of $X = [N_{mb}, N_{PV}, N_{WG}, N_{BAT}, h, \beta, W_{TANK}]$. The objective function to be minimized by the GA is equal to the sum of the capital and maintenance costs evolving during the desalination system lifetime period:

$$\begin{aligned} f(x) = {} & \left[CO_{Aq.RO} + 20.CO_{M.RO} + CO_{Aq.INV}(\tau_{INV} + 1) + CO_{M.INV}.(20 - \tau_{INV} - 1)\right] \\ & + N_{PV}\left(CO_{Aq.PV} + 20.CO_{M.PV}\right) + N_{WG}\left(CO_{Aq.WG} + 20.CO_{M.WG} + h.CO_{Aq.h} + 20.h.CO_{M.h}\right) \\ & + N_{BAT}.\left[CO_{Aq.BAT} + \tau_{BAT}.CO_{Aq.BAT} + (20 - \tau_{BAT} - 1).CO_{M.BAT})\right] \\ & + N_{ch}^{PV}.\left[CO_{Aq.ch}^{PV} + (\tau_{ch}^{PV} + 1) + CO_{M.ch}^{PV}.(20 - \tau_{ch}^{PV} - 1)\right] + V_{TANK}.\left[CO_{Aq.Tank} + 20.CO_{M.TANK}\right] \end{aligned} \tag{30}$$

with the following constraints:

$N_{mb} \geq 1; N_{PV} \geq 0; N_{WG} \geq 0; N_{BAT}/n_B^s \geq 1; V_{TANK} \geq 0;$ $h_{low} \leq h \leq h_{high}; 0 \leq \beta \leq 90^\circ$.

Where $CO_{Aq.RO}$, $CO_{Aq.PV}$, $CO_{Aq.WG}$, $CO_{Aq.BAT}$, $CO_{Aq.INV}$, $CO_{Aq.ch}^{PV}$, $CO_{Aq.Tank}$, and $CO_{Aq.h}$ are the capital costs of the RO desalination units, PV modules, W/Gs, batteries, DC/AC inverters, PV battery chargers, water storage tank (per m^3), and W/G installation tower (per m), respectively. $CO_{M.RO}$, $CO_{M.PV}$, $CO_{M.WG}$, $CO_{M.BAT}$, $CO_{M.INV}$, $CO_{M.ch}^{PV}$, $CO_{M.TANK}$, and $CO_{M.h}$ are the annual maintenance costs of the RO plant, PV modules, W/Gs, batteries, DC/AC inverters, PV battery chargers, water storage tank (per m^3), and W/G installation tower (per m), respectively. τ_{BAT} is the expected number of battery replacements during the 20-year system operation, because of limited battery lifetime and τ_{ch}^{PV} and τ_{INV} are the expected numbers of PV battery chargers and DC/AC inverters replacements during the system 20-year lifetime period, which are equal to the system lifetime period (20 years) divided by the Mean Time Between Failures of power electronic converters. Each of the capital costs incorporated in Eq. (30) incorporates the market price and the installation cost of the respective device.

Initially, a population of chromosomes is generated randomly and the constraints described by the inequalities Eq. (30) are evaluated for each chromosome. If any of the initial population chromosomes violates these constraints then it is replaced by a new, randomly generated chromosome, which fulfills these constraints. The first step of the GA-based optimal sizing algorithm iteration is the fitness function evaluation for each chromosome of the extracted population. If any of the resulting fitness function values is lower than the lowest value obtained at the previous iterations then this value is considered to be the optimal solution of the minimization problem and the corresponding chromosome's values are considered to be the desalination system's optimal sizing and operational parameters.

Table 2
Characteristics of the different components used in the model

RO membranes	Solar generator	Wind tubines	Batteries
Diameter = 8´´ , Active surface = 37 m^2 Recovery ~ 15% Salt reject = 99.5%	Nomminal power = 230 W I_{max} = 7.2 mA Module efficiency = 10% Module area = 1.18 m^2 Acquistion cost = 4.7US$/W	Rotor diameter = 6.7 Heigh = 18~43 m Rated power = 7.5 ~ 10 kW	Nominal capacity = 200 Ah Nominal voltage = 12 V DOD_{max} = 40% Efficiency = 80% Acquisition cost = 760US$

This optimal solution is replaced by better solutions, if any, produced in subsequent GA generations during the program evolution. The selection of the chromosomes, which will be subject to the crossover and mutation operations, thus producing the next generation population, is based on the roulette wheel method [33]. The crossover mechanism uses the Simple Crossover, Simple Arithmetical Crossover and Whole Arithmetical Crossover operators. Next, the selected chromosomes are subject to the mutation mechanism, which is performed using the Uniform Mutation, Boundary Mutation and Non-Uniform Mutation operators. In case that the application of the crossover or mutation operators result in a chromosome which does not satisfy the optimization problem constraints, then a "repair" procedure is performed and that chromosome is replaced by the corresponding parent. In case of the Simple Crossover operation, where each new chromosome is generated by two parents, then the chromosome is replaced by the parent with the best fitness function value. The GA optimization process described above is repeated until a predefined number of population generations have been evaluated.

4. Simulation results and discussion

The proposed methodology has been applied and tested for the design and optimal sizing of RO desalination systems power-supplied by PV and W/G energy sources located in the area of Ksar Ghilène Village (300 inhabitants), southern Tunisia at: latitude = 33.45°, longitude = 9.02° and altitude = 64 m above sea level. The average national water consumption in Tunisia is about 150 l/day/inhabitant. However, the RO unit is designed for primary needs consumption (drinking, cooking, etc.). Hence, a maximum daily water consumption of 50 l/day/inhabitant was assumed; giving 15 m^3/day as maximum total water needs.

To calculate the energy needs of the system, first we calculate the total power requirements for different subsystems, given the maximum operation hours of the RO system. In the present case the total energy demand for the RO plant is 558.03 Wh.

In the first iteration of the optimization methodology 20 individuals were generated. This population contains different PV/Wind combinations allowing to provide the water required by the village and the power to drive the RO plant.

The different characteristics of the components used in these simulations are summarized in Table 2.

From the chromosomes generated in the first step, a second generation is provided by using selection (30%), crossover (50%), and mutation (20%). We found that the minimum cost of water in the first generation was 3.56$/$m^3$. It decreased to 3.12$/m^3 in the second generation.

The variation of the water cost during the GA-based optimization process evolution is presented in Fig. 6.

This figure shows a significant decrease of the objective function CO_{Tot} for the first 30 generations and stabilizes around 2.62$/$m^3$. This means that the optimal solution is reached.

In the context of Ksar Ghilène Village the minimum cost corresponds to RO desalination plant driven by PV modules only. Fig. 7 presents the variation of the charge and discharge states of the batteries throughout the year.

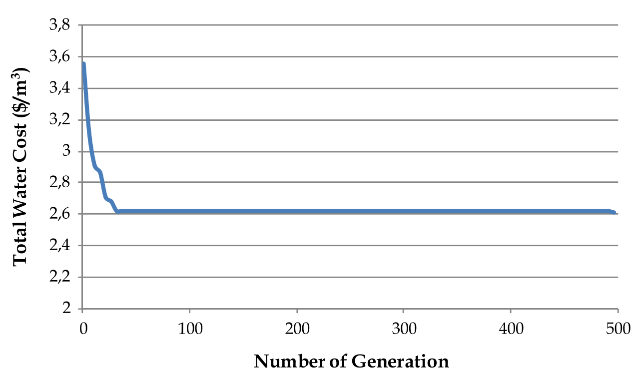

Fig. 6. The variation of the total cost function during the GA-based optimization process.

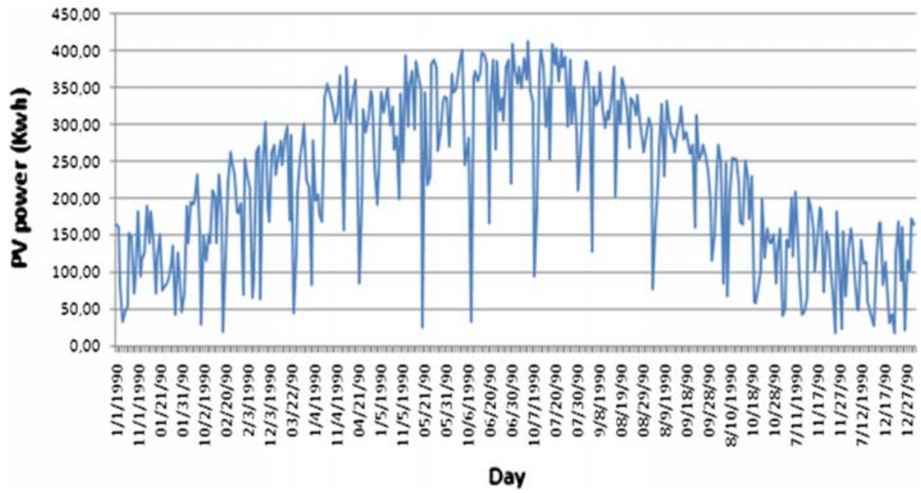

Fig. 7. Variation of the battery charges for the optimal solution.

In the optimal solution no W/G is considered since the village of Ksar Ghilène does not have a good potential for wind energy but a very interesting solar potential.

5. Conclusion

Several combinations for desalination processes driven by RE can be proposed to provide water and energy in remote areas (Solar/MSF, Solar/MED, PV/RO, etc.). RO is most often chosen as one of the most efficient desalination techniques in terms of energy consumption, flexibility, reliability, simple maintenance, etc.

There are a number of issues that should be taken into consideration while designing RES/RO systems as: the characteristics of water demand, the cost of water and fuel, the availability of RE resources, the initial cost of the project, including the cost of each component required, the life time of the project, the interest rate subsidies, etc. A techno-economic comparison between different scenarios can be carried out to study the feasibility of the project.

In this paper a new methodology to optimize RO desalination system driven by hybrid PV/Wind systems is presented. The proposed methodology is based on determining, among a list of commercially available system devices, the optimal number and type of units (PV modules, W/G, Batteries, etc.) such that the life time round total system cost is minimized, while simultaneously the desalinated-water demand is completely covered. The minimization of the system total cost function has been implemented using GAs that allows considering a large number of possible configurations.

The proposed method has been applied and tested for the design of a desalination system, which cover the potable water demands of a small community in South Tunisia. The application of this methodology allows to reduce the cost of the produced water from 3.56$/m^3 in the first generation to 2.62$/m^3 for the optimal solution. The fluctuation of the different costs during the GA-based optimization process shows that the capital cost of the system varies from 69 to 82% of the total cost. In all cases examined, a significant part of the desalination system's total capital cost is comprised of the cost of the batteries, which fluctuates between 17 and 32% depending on the PV module types and inclination.

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