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Design optimization of desalination systems power-supplied by PV and W/G energy sources

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ABSTRACT

In this paper, a methodology for the optimal sizing of desalination systems, power-supplied by Photovoltaic modules and Wind-Generators, is presented. 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 20-year round total system cost is minimized, while simultaneously the consumer's water demand is completely covered. The total cost function minimization is implemented using genetic algorithms, which have the ability to calculate the global optimum in the overall state space with relative computational simplicity. The proposed method has been applied for the design of desalination systems, which cover the potable water demands of a small community and of a residential household, respectively, in order to prove its effectiveness in various desalination system size scales. According to the corresponding optimal sizing results presented in this paper, the total cost of the desalination system is highly affected by the operational characteristics of the devices comprising the system, which affect the degree of exploitation of the available solar and wind energy potentials.

1. Introduction

Energy and water constitute two indispensable parameters for the existence and the advance of modern societies. However, only about 3% of all the water resources are potable, while about 25% of the world's population does not have access to adequate quality and quantity of fresh water [1]. Additionally, the availability of potable water resources is decreasing because of the worldwide climate change causing drought and desertification, the continuously increasing water demands, the population increase and the contamination of the existing water resources [2].

The application of water desalination processes offers a viable solution to the aforementioned problems. The water produced by a desalination system can be stored in large quantities and for long time periods at low cost. The Reverse Osmosis (RO) process is the most widely used desalination technology because of its ability to perform the water treatment with relatively low energy requirements and cost. The RO desalination systems can be used to perform both brackish and seawater desalination processing.

The use of renewable energy sources (RES) for power-supplying desalination systems is particularly favored in remote areas (e.g. islands), where the conventional electricity production is characterized by significant cost, while, additionally, these areas are usually characterized by significant RES potential coupled with lack of potable water resources [3,4]. Using RES in order to power-supply RO desalination systems enables the implementation of water production installations, which are characterized by high reliability and low maintenance requirements [5]. The block diagram of an RO desalination system, which is power-supplied by Photovoltaic (PV) and/or Wind-Generator (W/G) energy sources, is illustrated in Fig. 1.

Battery chargers, connected to a common DC bus, are used to charge the battery bank from the respective PV and W/G input power sources, which 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 (inverters) 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 drawn by the desalination system consumer.

The operational performance and the reliability of the desalination systems power-supplied by RES are affected by their proper design and sizing [6]. The optimal exploitation of the available RES potential is necessary in order to reduce the cost of the water produced.

An optimization strategy for the design and operation of a small-scale, solar-powered RO desalination system is presented in [7]. The optimal system design is targeting towards the minimization of the desalination unit energy consumption. The decision variables of the design process are the type of membrane, the membrane area, the recovery rate and the

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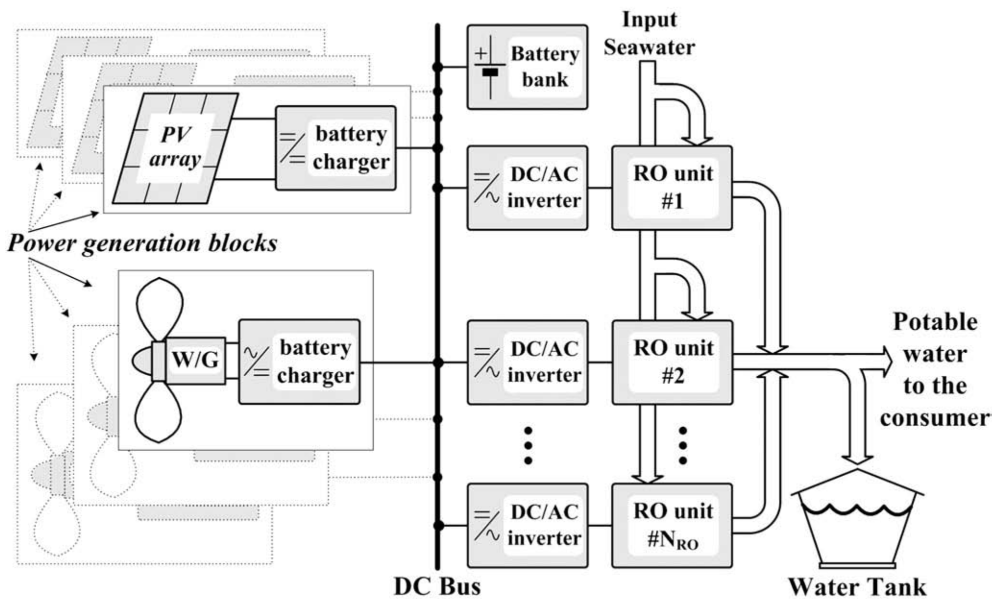

Fig. 1. The configuration of a desalination system power-supplied by PV and W/G energy sources.

efficiency of the high-pressure unit. However, the optimal design of the PV power generation system, which is used to power-supply the desalination unit, has not been addressed in this paper.

The PV–RO system design analyzed in [5] is based on an iterative procedure. 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. This design process does not include the optimization of the components' number and type and the minimization of the total system cost.

The wind power exploitation for assisting the operation of RO desalination plants is investigated in [8]. The desalination plants considered are power-supplied by one 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.

In Ref. [9], a computer-aided design tool is presented for the preliminary design of RES-powered desalination plants and the evaluation of the corresponding water production cost. The RES power production capability is determined using an iterative procedure, such that an energy balance is achieved between the energy produced by the RES and the auxiliary energy sources (e.g. electric grid, diesel generators etc.) and the energy demand of the desalination unit. However, this design method does not include the economic optimization of the resulting configurations.

The development and application of a software tool for designing hybrid RES systems consisting of a W/G and PV modules, which are used to cover the electricity and water needs of remote areas, are presented in Ref. [10]. 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, such that the electric energy and water requirements are satisfied. The battery bank is sized such that several days of energy autonomy of the system is taken into account, 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 so as the water requirements are satisfied, even during the time periods of low RES potential availability.

The design of a stand-alone, hybrid wind/PV system, which is used to power-supply a seawater RO desalination unit, based on a techno-economic analysis, is proposed in Ref. [11]. The system contains both a battery bank and a produced water storage tank, in order to cover the potable water demand during the days with negligible solar and/or wind energy production. The design methodology is based on the RO unit sizing according to the maximum daily water demand, dictating the corresponding maximum total power requirements. Then, 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 calculated such that it is able to store the electric energy required for two days. The produced water storage tank volume is computed such that it provides a two summer day autonomy. In order to minimize the total system cost, the developed software calculates the portion of the daily energy produced by the previously sized PV system that will be replaced by the corresponding energy production of one or more W/Gs. This calculation is performed for various combinations of PV and W/G contribution percentages to the hybrid system total energy production and the combination achieving the minimum water production cost is selected as the final hybrid system configuration.

A methodology for the design of an autonomous RES system with fuel cell as the backup generator, in order to supply electricity to an RO desalination plant, is analyzed in Ref. [12]. The total energy generated by the RES and fuel cell units during the year is calculated for all combinations of the values of the total number of W/Gs, PV modules and fuel cells and it is compared with the corresponding electric energy requirements of the desalination plant. Then, a trade-off method is applied in order to choose the best system configuration in terms of the generated-electricity cost and the system reliability.

In this paper, an alternative methodology for the optimal sizing of desalination systems power-supplied by PV and W/G energy sources is proposed. 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 20-year round total system cost is minimized, while simultaneously the desalinated-water requirements of the consumer are completely covered. The 20-year round total system cost is equal to the sum of the respective components capital and maintenance costs. The decision variables included in the optimization process are the number and type of RO desalination units, the number and type of PV modules, W/Gs, battery chargers, DC/AC inverters and batteries, the PV modules tilt angle, the installation height of the W/Gs and the total volume of the desalinated-water storage tank. Compared to the past-proposed methodologies, which have been used in order to design water desalination systems power-supplied by RES, the methodology presented in this paper has the advantage that it takes 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 minimization of the system total cost function has been implemented using genetic algorithms (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 proposed methodology can be applied to implement the optimal sizing process of desalination systems, irrespectively of their size scale.

This paper is organized as follows: the proposed methodology is outlined in Section 2, the desalination system modeling and operation simulation are described in Section 3, the system total cost minimization using GAs is analyzed in Section 4 and the simulation results are presented and discussed in Section 5.

2. The proposed method

The proposed optimization methodology is outlined in the general block diagram depicted in Fig. 2. A database containing the technical characteristics of commercially available system devices, along with their associated per unit capital and maintenance costs, is input to the optimization algorithm. This database, which is implemented in the form of text files for easy maintenance, contains various types of RO desalination units, PV modules and W/Gs, batteries with different nominal capacities etc. The input (feed) and the desalinated water quality specifications of the RO desalination units included in the database must comply with the corresponding requirements set by the desalination system users.

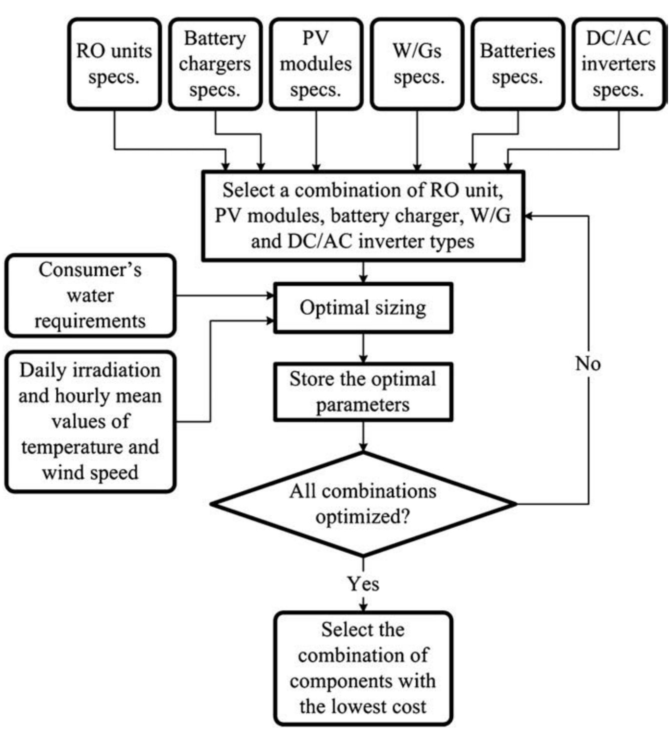

Fig. 2. The flowchart of the proposed optimization methodology.

At the first step of the optimal sizing methodology, a simulation of the system operation is performed in order to examine whether a system configuration, comprising a certain number of system devices and installation details, fulfils the consumer's desalinated-water requirements during the year. The data used in this case are the daily solar irradiation on horizontal plane, the hourly mean values of ambient temperature and wind speed and the consumer's water demand on a yearly basis. During the second step of the optimal sizing procedure, 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.

The optimal sizing procedure described above is applied to all device type combinations, computing the corresponding optimal total system cost and devices configuration. Then, the combination achieving the lowest total cost and the corresponding devices mixture are selected as the overall optimal system configuration.

3. The desalination system modeling and operation simulation

During the application of the proposed optimization methodology, the system operation is simulated for one year with a time step of one hour. 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 with the corresponding energy and water volume, respectively.

Each PV power generation block shown in Fig. 1, consists of N_P PV modules connected in parallel and N_S PV modules connected in series. The maximum output power of each PV power generation block on day i ($1 \le i \le 365$) and at hour t ($1 \le t \le 24$), $P_M^i(t, \beta)$ (W), is calculated using the specifications of the PV module under Standard Test Conditions (STC, cell temperature = 25 °C and solar irradiance = 1 kW/m^2), provided by the manufacturer, as well as the ambient temperature and solar irradiation conditions, according to the following equations:

$$P_M^i(t,\beta) = N_S \cdot N_P \cdot V_{OC}^i(t) \cdot I_{SC}^i(t,\beta) \cdot FF^i(t) \quad (1)$$

$$I_{SC}^i(t,\beta) = \left\{ I_{SC,STC} + K_I \cdot \left[T_C^i(t) - 25\,^\circ\mathrm{C} \right] \right\} \cdot \frac{G^i(t,\beta)}{1000} \quad (2)$$

$$V_{OC}^i(t) = V_{OC,STC} - K_V \cdot \left[T_C^i(t) - 25\,^\circ\mathrm{C} \right] \quad (3)$$

$$T_C^i(t) = T_A^i(t) + \frac{NOCT - 20\,^\circ\mathrm{C}}{800} \cdot G^i(t,\beta) \quad (4)$$

where $I_{SC}^i(t, \beta)$ is the PV module short-circuit current (A), $I_{SC,STC}$ is the short-circuit current under STC (A), $G^i(t,\beta)$ 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/°C), $V_{OC}^i(t)$ is the open-circuit voltage (V), $V_{OC,STC}$ is the open-circuit voltage under STC (V), K_V is the open-circuit voltage temperature coefficient (V/°C), $T_A^i(t)$ is the ambient temperature (°C), NOCT is the Nominal Operating Cell Temperature (°C), provided by the manufacturer and $FF^i(t)$is the Fill Factor [13].

The number of PV modules connected in series in each PV power generation block, N_S, is computed according to the battery charger maximum input voltage,V_{DC}^m (V), and the PV modules maximum open-circuit voltage level, V_{OC}^m (V):

$$N_S = \frac{V_{DC}^m}{V_{OC}^m} \quad (5)$$

The system designer is able to define the PV modules tilt angle to be either constant during the year, β, or variable with angle β_1 corresponding to the months from January until April (day numbers 1 to 104) and September until December (day numbers 290 to 365) and β_2 corresponding to the rest of the year. The value of $G^i(t, \beta)$ is calculated using the values of the daily solar irradiation on the horizontal plane according to the methodology analyzed in [14].

The PV power actually transferred to the battery bank by each PV power generation block, $P^i_{PV}(t, \beta)$ (W), is related to the maximum output power of the PV array, $P^i_M(t, \beta)$, through the battery charger power conversion factor, n_s, which is defined as follows:

$$n_s \equiv \frac{P^i_{PV}(t,\beta)}{P^i_M(t,\beta)} = n_1 \cdot n_2 \tag{6}$$

where 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 [15], 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.

The total number of PV battery chargers, N^{PV}_{ch}, depends on the total number of PV modules, N_{PV}, the power rating of the selected battery charger, P^m_{ch} (W) and the maximum power of one PV module under STC, P^m_{PV} (W), both specified by their manufacturers, according to the following equation:

$$N^{PV}_{ch} = \frac{N_{PV} \cdot P^m_{PV}}{P^m_{ch}} \tag{7}$$

The total number of PV battery chargers is equal to the total number of PV power generation blocks, which comprise the PV energy production and management subsystem.

The variation of the W/G output power versus the wind speed is provided by the manufacturer and 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, $P^i_{WG}(t, h)$ (W), is calculated using the following linear relation:

$$P^i_{WG}(t,h) = P_1 + \left[v^i(t,h) - v_1\right] \cdot \frac{P_2 - P_1}{v_2 - v_1} \tag{8}$$

where h (m) is the W/G installation height, $v^i(t, h)$ is the wind speed (m/s) at height h ($h_{low} \le h \le h_{high}$ 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 $[v_1 < v^i(t,h) < v_2]$ stored in the form of a lookup table, which is the input to the optimization algorithm.

The wind speed data input to the optimal sizing algorithm are usually measured at a different height than the desired W/G installation height, h. Thus, $v^i(t, h)$ is calculated using the following exponential law:

$$v^i(t,h) = v^i_{ref}(t) \cdot \left(\frac{h}{h_{ref}}\right)^{\alpha} \tag{9}$$

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.

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):

$$n^S_B = \frac{V_{BUS}}{V_B}. \tag{10}$$

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), as follows:

$$C_n = \frac{N_{BAT}}{n^S_B} \cdot C_B. \tag{11}$$

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 according to:

$$C_{min} = DOD \cdot C_n \tag{12}$$

The available battery bank capacity is modified during the desalination system operation according to the PV and W/G energy production levels and the power requirements of the desalination units, as follows:

$$C^i(t) = C^i(t-1) + n_B \cdot \frac{P^i_B(t)}{V_{BUS}} \cdot \Delta t \tag{13}$$

$$C^i(24) = C^{i+1}(0) \tag{14}$$

where $C^i(t)$, $C^i(t-1)$ is the available battery capacity (Ah) at hour t and $t-1$, respectively, of day i, $n_B = 80\%$ is the battery round-trip efficiency during charging and $n_B = 100\%$ during discharging [16], 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, set to $\Delta t = 1$ h.

The maximum permissible battery bank charging or discharging current has been limited to C_n/5 h in order to avoid the battery performance degradation under practical operating conditions. The initial capacity of the battery bank, $C^1(0)$, is calculated using the following equation:

$$C^1(0) = \left(\frac{1 - DOD}{2}\right) \cdot C_n \tag{15}$$

The PV and W/G energy sources must be sized such that they produce adequate energy during the year in order to completely satisfy the desalination system energy requirements. Thus, the remaining battery bank capacity at the end of the simulation period must be higher than its initial value:

$$C^{365}(24) \ge C^1(0). \tag{16}$$

The RO units are power-supplied by the PV and W/G energy sources and the battery bank. 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 must be performed, using flushing techniques. The total power produced by the PV and W/G energy sources at hour t of day i is calculated as follows:

$$P^i_{RE}(t) = N^{PV}_{ch} \cdot n_s \cdot P^i_M(t,\beta) + N_{WG} \cdot P^i_{WG}(t,h) \tag{17}$$

where N_{WG} is the total number of W/G power generation blocks incorporated in the desalination system.

The total DC power input to the DC/AC inverters at hour t of day i, $P^i_L(t)$ (W), is related with the total AC power supplying the desalination units, $P^i_{RO}(t)$ (W), according to the following equation:

$$P^i_L(t) = \frac{P^i_{RO}(t)}{n_i} = \frac{N_{RO} \cdot P^i_u(t)}{n_i} \tag{18}$$

where n_i (%) is the power conversion efficiency of the DC/AC inverters, N_{RO} is the number of desalination units and P_u^i (t) is the AC power consumption of each RO unit.

The total volume of desalinated water produced by the system desalination units at hour t of day i, W_{RO}^i (t) in m^3, is computed according to the water production of each RO unit, W_u^i (t) (m^3), as follows:

$$W_{RO}^i(t) = N_{RO} \cdot W_u^i(t). \tag{19}$$

The minimum permissible amount of water stored in the tank, W_{min} (m^3), has been set equal to 30% of the tank total volume, W_{TANK} (m^3):

$$W_{min} = 0.3 \cdot W_{TANK}. \tag{20}$$

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

$$W_{min} \le W^i(t) \le W_{TANK}. \tag{21}$$

Each time that a flushing process is performed in order to clean the membranes of the RO units, then the total consumed amounts of the AC power, P_{FL} (W) and of the water stored in the tank, W_{FL} (m^3), are calculated as follows:

$$P_{FL} = N_{RO} \cdot P_{u,FL} \tag{22}$$

$$W_{FL} = N_{RO} \cdot W_{u,FL} \tag{23}$$

where $P_{u,FL}$ (W) and $W_{u,FL}$ (m^3) are the power and water consumptions, respectively, of each RO unit during the flushing process.

Defining the desalination system consumer's water demand at hour t of day i as W_D^i (t) (m^3), then the energy and water flows among the system subunits are described as follows:

- If P_{RE}^i $(t) \ge P_L^i$ (t) and W_{RO}^i $(t) = W_D^i$ (t), then the battery bank is charged by $P_{RE}^i(t) - P_L^i(t)$ and the amount of the water stored in the water tank remains constant.
- If P_{RE}^i $(t) \ge P_L^i$ (t) and W_{RO}^i $(t) > W_D^i$ (t), then the battery bank is charged by $P_{RE}^i(t) - P_L^i(t)$ and the water surplus $W_{RO}^i(t) - W_D^i(t)$ is stored in the water tank.
- If P_{RE}^i $(t) \ge P_L^i$ (t) and W_{RO}^i $(t) < W_D^i$ (t), then the battery bank is charged by $P_{RE}^i(t) - P_L^i(t)$ and the remaining water demand $W_D^i(t) - W_{RO}^i(t)$ is covered by the water stored in the tank. In case that the volume of water stored in the tank is not enough to cover the consumer's requirements, then the system operation is considered to be unsuccessful.
- If $P_{RE}^i(t) < P_L^i(t)$ and adequate energy is stored in the battery bank in order to power-supply the desalination units, then the battery bank is discharged by $P_L^i(t) - P_{RE}^i(t)$ and
  - If W_{RO}^i $(t) = W_D^i$ (t), then the volume of the water stored in the tank remains constant.
  - If W_{RO}^i $(t) > W_D^i$ (t), then the water surplus, $W_{RO}^i(t) - W_D^i$ (t) is stored in the water tank.
  - If W_{RO}^i $(t) < W_D^i$ (t), then the remaining water demand, $W_D^i(t) - W_{RO}^i(t)$, is covered by the water stored in the water tank. In case that the volume of the water stored in the tank is not enough to cover the consumer's requirements, then the system operation is considered to be unsuccessful.
- If P_{RE}^i $(t) < P_L^i$ (t) and the energy stored in the battery bank is not adequate to support the operation of the desalination units, then the desalination units are turned off and:
  - If the water stored in the tank is enough in order to cover the consumer's demand, then the water tank is discharged by W_D^i (t) and the battery bank is charged by $P_{RE}^i(t)$. Moreover, if the energy stored in the battery bank is adequate to perform the flushing process, then the battery bank is discharged by P_{FL}, otherwise, the flushing process is postponed.
  - If the water stored in the tank is not enough to cover the consumer's water demand, then the system operation is considered to be unsuccessful.

The desalination system modeling described above, is used to simulate the system operation on a yearly basis. It is incorporated into the GA optimization procedure in order to evaluate the feasibility of the optimal sizing problem's potential solutions, as analyzed in the next Section.

4. System total cost minimization using GAs

In the proposed methodology, the genetic algorithms (GAs) are used for designing and sizing a desalination plant powered by PV modules and W/Gs, 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. It works with a fixed-size population of possible solutions of a problem, which are evolving in time. A genetic algorithm utilizes three principal genetic operators; selection, crossover and mutation. Compared to conventional optimization methods, such as dynamic programming and gradient techniques, genetic algorithms 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 [17].

In case that the PV modules tilt angle is constant during the year, then the GA chromosomes are in the form of $\mathbf{X} = [N_{PV}|N_{WG}|N_{BAT}|h|\beta|W_{TANK}|N_{RO}]$, while in case that the PV modules are installed at two different tilt angles during the year, then the form of each chromosome is $\mathbf{X} = [N_{PV}|N_{WG}|N_{BAT}|h|\beta_1|\beta_2|W_{TANK}|N_{RO}]$. The chromosomes do not include the number of PV battery chargers and the number of DC/AC inverters, since their values are dictated by N_{PV} and N_{RO}, respectively.

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:

$$\begin{aligned} g(\mathbf{X}) = {} & N_{PV} \cdot (C_{PV} + 20 \cdot M_{PV}) + N_{WG} \cdot (C_{WG} + 20 \cdot M_{WG} + h \cdot C_h + 20 \cdot h \cdot M_h) \\ & + N_{BAT} \cdot [C_{BAT} + Y_{BAT} \cdot C_{BAT} + (20 - Y_{BAT} - 1) \cdot M_{BAT}] + N_{ch}^{PV} \\ & \times \left[C_{ch}^{PV} \cdot \left(Y_{ch}^{PV} + 1\right) + M_{ch}^{PV} \cdot \left(20 - Y_{ch}^{PV} - 1\right)\right] + W_{TANK} \\ & \times [C_{TANK} + 20 \cdot M_{TANK}] + N_{RO} \cdot [C_{RO} + 20 \cdot M_{RO} + C_{INV} \cdot (Y_{INV} + 1) \\ & + M_{INV} \cdot (20 - Y_{INV} - 1)] \end{aligned} \tag{24}$$

where C_{PV}, C_{WG}, C_{BAT}, C_{INV}, C_{ch}^{PV}, C_{TANK}, C_{RO} and C_h are the capital costs of the PV modules, W/Gs, batteries, DC/AC inverters, PV battery chargers, water storage tank (per m^3), RO desalination units and W/G installation tower (per m), respectively, M_{PV}, M_{WG}, M_{BAT}, M_{INV}, M_{ch}^{PV}, M_{TANK}, M_{RO} and M_h are the annual maintenance costs of the PV modules, W/Gs, batteries, DC/AC inverters, PV battery chargers, water storage tank (per m^3), RO desalination units and W/G installation tower (per m), respectively, Y_{BAT} is the expected number of battery replacements during the 20-year system operation, because of limited battery lifetime and $Y_{ch}^{PV}$and Y_{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 (MTBF) of power electronic converters.

Each of the capital costs incorporated in Eq. (24) incorporates the market price and the installation cost of the respective device. The quality of both the input (feed) water and the desalinated water affect the cost of the RO desalination units, C_{RO}, since they determine the corresponding operational specifications of the Reverse Osmosis units, which must be used.

Since this GA problem is a minimization problem, the following transformation is performed:

$$f(\mathbf{X}) = \begin{cases} C_{max} - g(X), & \text{if } C_{max} > g(X) \\ 0, \text{else} \end{cases} \tag{25}$$

where $f(\mathbf{X})$ is the genetic algorithms' fitness function, used for the selection of the chromosomes that will participate in the crossover and mutation operations according to the roulette wheel method and C_{max} is the absolute value of the minimum value of the g(·) function, calculated at each new generation [17].

Therefore, the optimization problem is defined as follows:

maximize $f(\mathbf{X})$

subject to the following constraints:

$$\begin{aligned} & N_{PV} \geq 0, N_{WG} \geq 0, N_{BAT} / n_B^S \geq 1, W_{TANK} \geq 0, N_{RO} \geq 1, \\ & h_{low} \leq h \leq h_{high}, 0^\circ \leq \beta \leq 90^\circ \text{ or} \\ & [0^\circ \leq \beta_1 \leq 90^\circ \text{ and } 0^\circ \leq \beta_2 \leq 90^\circ] \quad \text{and} \\ & \text{Simulation}(\mathbf{X}) = \text{Successful}. \end{aligned} \tag{26}$$

The Simulation (·) function performs the simulation of the desalination system operation, according to the modeling presented in Section 3, in order to verify that the system configuration under examination fulfils the desalinated-water requirements of the consumer, thus guaranteeing the successful system operation during the whole year. In case that any of the optimization problem constraints described above is not satisfied, then the specific chromosome containing the corresponding genes is rejected.

Initially, a population of 30 chromosomes, comprising the 1st generation, is generated randomly and the constraints described by the inequalities (Eq. (26)) 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 fulfils 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. 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 [17]. 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 results 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.

5. Simulation results and discussion

The proposed methodology, which has been presented in Sections 2–4, 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 the Technical University of Crete (TUC) with geographical coordinates defined as: latitude = 35.53° (35° 31′ 48″ N), longitude = 24.06° (24° 03′ 35″ E) and altitude = 150 m (approx.) above sea level. The corresponding optimal sizing and operational simulation results are presented in the following paragraphs. The methodology is tested for both a unique residential household and a community of 15 houses located in the specific area, in order to prove its effectiveness in various desalination system size scales.

5.1. Simulation parameters

The installation area's ground surface albedo is equal to 0.2 and the value of the wind speed law exponent is $\alpha = 0.2$. The meteorological conditions during the year, i.e. the daily solar irradiation on horizontal plane and the hourly mean values of the air temperature and the wind speed of the specific location are illustrated in Fig. 3.

The daily water demand during the year, of a residential household located in the installation area, is illustrated in Fig. 4. The corresponding diurnal variation during a winter day is depicted in Fig. 5. The water demand takes its maximum value during the early evening

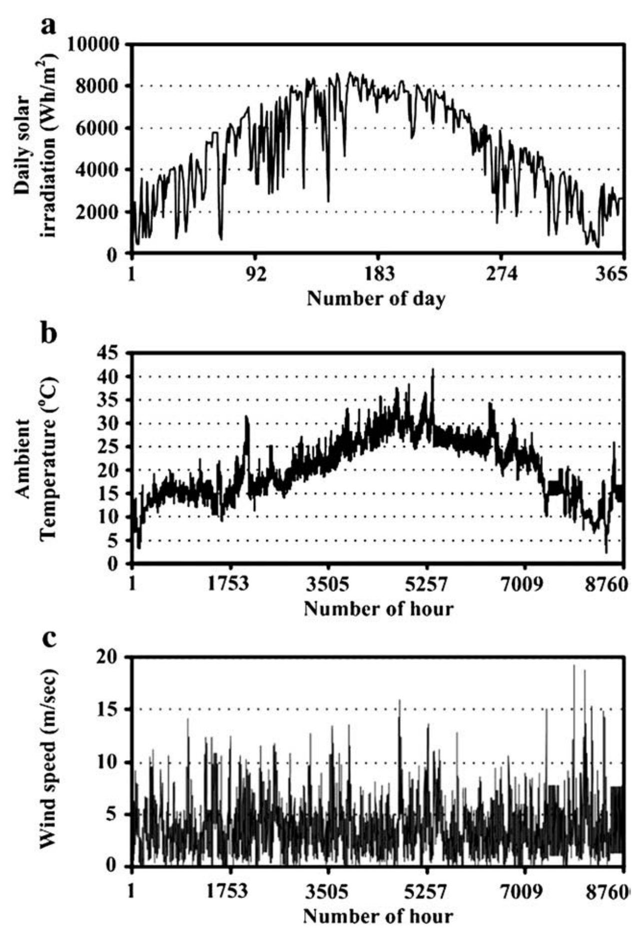

Fig. 3. The meteorological conditions of the specific location during the year: (a) the daily solar radiation on horizontal plane, (b) the hourly mean values of the air temperature and (c) the hourly mean values of the wind speed.

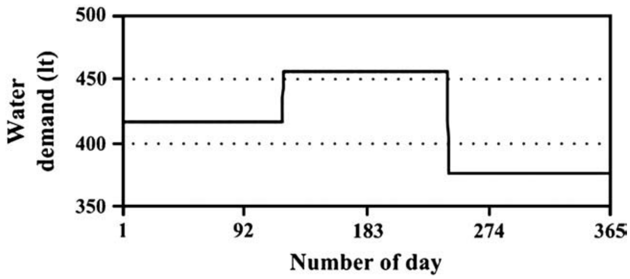

Fig. 4. The daily water demand of a residential household during the year.

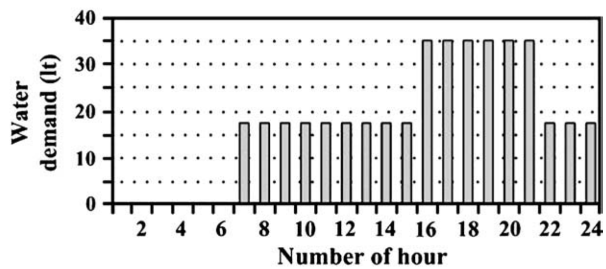

Fig. 5. The diurnal variation of the water demand of a residential household during a winter day.

hours, while during nighttime is equal to zero. During the rest of the year, the diurnal variation follows the same pattern, but it is scaled according to the daily water demand presented in Fig. 4.

The GA parameters used for the implementation of the optimal sizing procedure are: number of chromosomes per generation $N = 30$, simple crossover probability $p_{sc} = 0.1$, simple arithmetic crossover probability $p_{sac} = 0.1$, whole arithmetic crossover probability $p_{wac} = 0.1$, uniform mutation probability $p_{um} = 0.1$, boundary mutation probability $p_{bm} = 0.03$ and non-uniform mutation probability $p_{nm} = 0.35$. The GA procedure is executed for 20,000 generations. Finally, the types and the respective technical and economical characteristics of the various desalination system components used in the optimal sizing procedure, are presented in Tables 1–6. These devices are commercially available and they are typically used in desalination systems applications. The RO desalination unit, which has been included in the optimal sizing procedure, produces potable water and it is power-supplied by a 220 V/50 Hz power source. Its power consumption and water production operational characteristics are tabulated in Table 6. The selection of the specific system components has been based on their technical characteristics, such that the features and the capabilities of the proposed optimal sizing methodology are demonstrated by the corresponding simulation results. However, the list of components included in each of these tables can be extended by the system designer according to the availability of system components in the local or international market. The capital and annual maintenance costs of the water storage tank have been set equal to $C_{TANK} = 260€/m^3$ and $M_{TANK} = 1€/m^3$/year, respectively. The MTBF of the PV battery chargers and the DC/AC inverters has been set equal to 40,000 h. The expected operational lifetime period of the batteries has been set at 3 years resulting in $Y_{BAT} = 6$.

Table 1
The technical and economical characteristics of the PV modules.

Type	V_{oc} (V)	I_{sc} (A)	V_{max} (V)	I_{max} (A)	P_{max} (watt)	NCOT (°C)	C_{PV} (€)	M_{PV} (€/year)
T1	21.6	3.48	17.3	3.18	55	43	265.81	2.66
T2	21	7.22	17	6.47	110	43	519.14	5.19

Table 2
The technical and economical characteristics of the W/G.

$P_{WG,max}$ (watt)	h_{low} (m)	h_{high} (m)	C_{WG} (€)	M_{WG} (€/year)	C_h (€/m)	M_h (€/year/m)
1000	8	15	1681	16.81	55	0.55

Table 3
The technical and economical characteristics of the batteries.

Type	C_B (Ah)	V_B (V)	DOD (%)	C_{BAT} (€)	M_{BAT} (€/year)
T1	230	12	80	264	2.64
T2	100	12	80	126	1.26

Table 4
The technical and economical characteristics of the PV battery chargers.

Type	n_1 (%)	n_2 (%)	P_{ch}^{m} (watt)	C_{ch}^{PV} (€)	M_{ch}^{PV} (€/year)
T1	96	100	300	200.0	2.0
T2	96	70	240	94.0	0.94

Table 5
The technical and economical characteristics of the DC/AC inverter.

n_i (%)	$P_{L,max}$ (watt)	C_{INV} (€)	M_{INV} (€/year)
90	5000	453.0	45.3

Table 6
The technical and economical characteristics of the RO desalination unit.

W_u (l/day)	P_u (W)	$W_{u,FL}$ (l)	$P_{u,FL}$ (W)	C_{RO} (€)	M_{RO} (€/year)
11,400	1120	79.5	190.4	4667.97	466.8

5.2. The optimal sizing results

5.2.1. Sizing of a desalination system for a community

The GA-based optimal sizing procedure has been applied for the design of a desalination system covering the water demands of a community, which is formed by 15 residential households, each having the water demand patterns depicted in Figs. 4 and 5. The values of the optimal total system cost, for various types of PV modules, batteries and PV battery chargers, in case that the PV modules tilt angle is constant during the year, are presented in Table 7.

The maximum difference among the various combinations is equal to €14,263.6. The overall optimum configuration, having a total system cost equal to €133,473.63, consists of 26 PV modules distributed among 9 PV power generation blocks, each interfaced to the battery bank through the respective battery charger, 15 W/Gs, 1

Table 7
The total system cost of the community's desalination system for various system device types, in case that the PV modules tilt angle is constant during the year.

PV module type	Battery type	PV battery charger type	Optimal cost (€)
T1	T1	T1	139,859.20
T1	T1	T2	139,946.68
T1	T2	T1	143,659.70
T1	T2	T2	147,385.81
T2	T1	T1	133,473.63
T2	T1	T2	142,042.33
T2	T2	T1	136,559.41
T2	T2	T2	147,737.29

Table 8
The optimal sizing results for the community's desalination system in case of one and two PV module tilt angles during the year.

	One tilt angle		Two tilt angles	
	Type	Total number	Type	Total number
PV modules	T2	26	T2	26
W/G	T1	15	T1	15
Batteries	T1	12	T1	12
DC/AC inverter	T1	1	T1	1
Battery chargers	T1	9	T1	9
RO units	T1	1	T1	1
h (m)	13		13	
β (°)	34		$\beta_1 = 34°$and $\beta_2 = 0°$	
V_{BUS} (volt)	24		24	
Water tank (l)	9828		9592	
Total cost (€)	133,473.63		133,407.55	

RO desalination unit, 12 batteries and 1 DC/AC inverter, as tabulated in Table 8.

As illustrated in Fig. 6, the most expensive component of the optimum solution is the batteries contributing by 35% to the total system cost, while the least expensive units are the DC/AC inverter and the water tank, each contributing by 2% to the total cost. The capital cost of all system devices corresponds to 84% of the total system cost, which is mainly attributed to the required periodic replacement of the batteries, while the maintenance cost contributes to the rest 16%.

The variation of the battery bank state of charge during the year is illustrated in Fig. 7. The battery bank maximum depth of discharge is 80%. Thus, using the resulting optimally sized desalination system enables both the reliable power-supply of the RO desalination unit and the full exploitation of the battery bank energy storage capability, contributing towards the minimization of the total system cost.

The fluctuation of the volume of the water stored in the tank during the year is depicted in Fig. 8. It is observed that the water volume is kept above 8500 l for the whole year, except aproximately10 days where it drops below 4000 l. Therefore, the optimally sized desalination system is capable to completely cover the community's water demand.

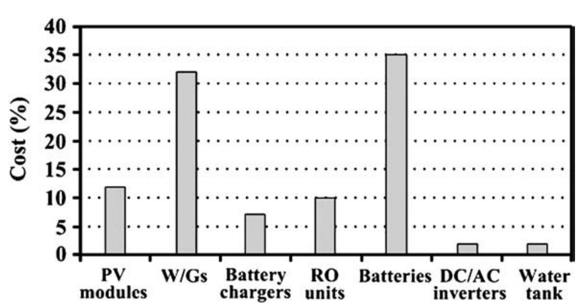

Fig. 6. The contribution of the various components cost to the total capital and maintenance cost for the community's desalination system, in case that the PV modules tilt angle is constant during the year.

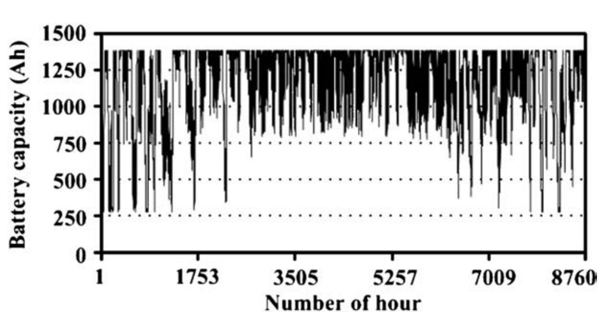

Fig. 7. The variation of the battery bank state of charge during the year.

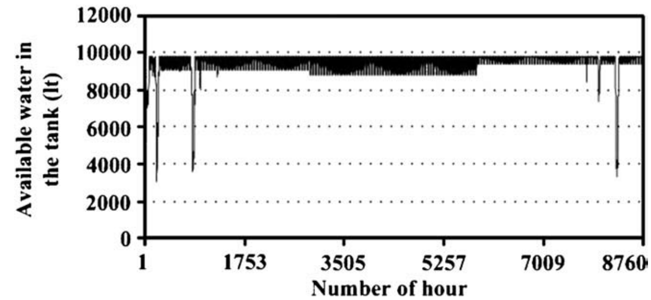

Fig. 8. The fluctuation of the volume of the water stored in the tank during the year.

The optimal desalination system configuration in case that the PV modules are installed at two different tilt angles during the year is presented in Table 8. The total system cost is slightly lower compared to the total system cost resulting in case that the PV modules tilt angle is constant during the year, due to the lower water storage tank volume required, since a better exploitation of the available solar irradiation potential is achieved in this case. The maximum difference among the optimal total costs of the various combinations of system device types is equal to €12,513.34, almost €2000 lower than in the previous case.

In all of the optimal sizing results presented above, the optimal devices mixture contains the PV battery charger type T1, which is equipped with an MPPT capability, since, although it is of higher capital cost, it achieves a better exploitation of the installed PV modules power production capability.

5.2.2. Sizing of a desalination system for a single residential household

The proposed GA-based optimal sizing procedure has also been used to design a desalination system, which covers the water requirements of a single residential household, in case of both one and two PV modules' tilt angle values during the year. The corresponding optimal sizing results are tabulated in Table 9. It is observed that using two PV modules tilt angle values during the year results in a lower total system cost due to the better exploitation of the available solar energy. In both cases, the optimal devices mixture contains the PV battery charger type T1 (it is equipped with an MPPT capability) since, although it is of higher capital cost, it achieves a better exploitation of the installed PV modules power production capability. Thus, in case that the PV modules are installed with two different tilt angles during the year, the RO units power demand is covered by 6 wind turbines instead of 7.

Both the battery bank and the water tank contribute to the satisfaction of the consumer's water demand during the time periods with low RES energy production. According to the optimal sizing

Table 9
The optimal sizing results for the residential household's desalination system in case of one and two PV module tilt angles during the year.

	One tilt angle		Two tilt angles	
	Type	Total number	Type	Total number
PV modules	T2	7	T2	7
W/G	T1	7	T1	6
Batteries	T1	2	T1	2
DC/AC inverter	T1	1	T1	1
Battery chargers	T1	2	T1	2
RO units	T1	1	T1	1
h (m)	11		14	
β (°)	39		$\beta_1 = 46°$and $\beta_2 = 11°$	
V_{BUS} (volt)	24		24	
Water tank (l)	6400		6862	
Total cost (€)	51,892.13		50,466.29	

results presented in Table 9, the use of a water tank with relatively large volume is favored, due to its low capital and maintenance costs, instead of increasing the number of batteries comprising the battery bank.

The capital cost of the system components corresponds to approximately 72% of the total system cost, while the maintenance cost contributes to the rest 28%, irrespectively of the number (one or two) of possible PV modules tilt angles during the year.

Comparing the optimal sizing results presented in Tables 8 and 9, it is observed that the total cost per residential household in the community's desalination system is much lower than the corresponding cost of the desalination system designed for a single residential household, due to the efficient exploitation of the operational characteristics of the available system devices comprising the desalination system, which is achieved in the former case.

5.3. Alternative power-supply configurations

The optimal sizing results in case that the power source supplying the residential household's and the community's desalination systems, respectively, consists either only of PV modules, or only of W/Gs, are presented in summary in Table 10. The hybrid power system is the most economically attractive, irrespectively of the desalination system size scale, compared to the other two configurations. This is due to the considerably higher number of PV modules and PV battery chargers required to implement the only-PV system and the increased number of W/Gs and batteries (only in the case of the community's desalination system) needed to cover the power demand for the only-W/G system, under the specific region's solar radiation and wind speed conditions. For the community's desalination system, comparing the PV modules optimal tilt angle values, which result for the only-PV and the hybrid power sources, respectively, it is observed that the PV modules optimal tilt angle value is much lower in the first case. This is due to the maximization of the community's water demand during the summer time period, necessitating the reduction of the PV modules tilt angle in order to maximize the corresponding PV energy production. In the hybrid power system configuration, also for the community's desalination system, the PV modules optimal tilt angle is higher, thus enhancing the PV energy production during the winter time period, while the resulting energy deficit during the summer is compensated by the contribution of the W/G energy sources to the total energy production.

5.4. The total cost function used in the optimization process

The total cost function versus the number of PV modules and W/Gs, in case that the sizing procedure is applied for the design of a single residential household's desalination system using a constant PV modules tilt angle during the year and $N_{BAT}=2$, $N_{RO}=1$, $C_n=230$Ah, $h=11$ m, $\beta=39°$ and $W_{TANK}=6400$ l, is illustrated in Fig. 9(a). Although the cost function contains a significant number of local minima, applying the proposed GA-based optimal sizing procedure results in convergence to the global minimum point (also verified using an exhaustive search algorithm), thus proving the corresponding computing ability of genetic algorithms. The variation of the total cost function, during the GA-based optimization process evolution, is depicted in Fig. 9(b). It is observed that a near-optimal solution has already been derived at the early stages of the optimization procedure.

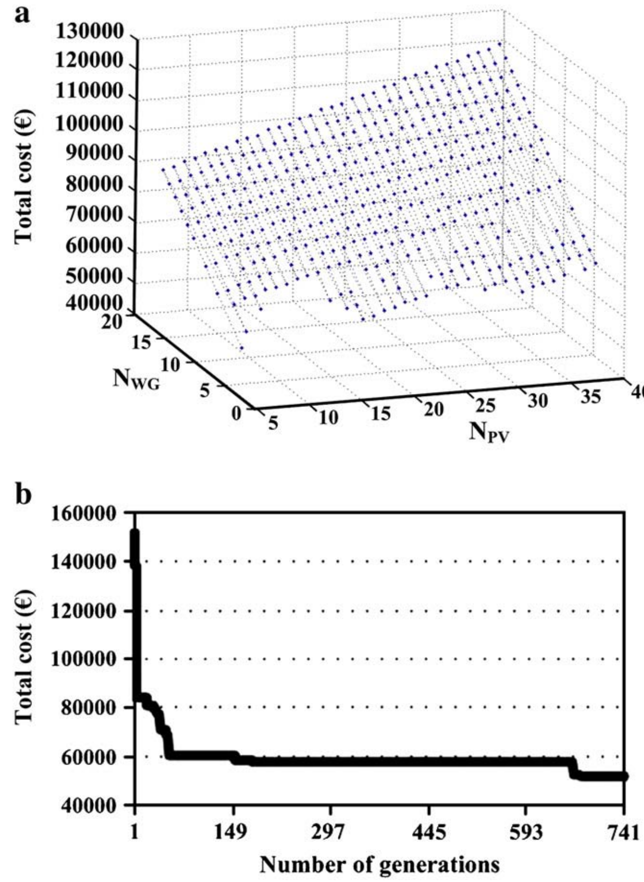

Fig. 9. The variation of the total cost function value in case that the sizing procedure is applied for the design of a single residential household's desalination system using a constant PV modules tilt angle during the year, versus: (a) the number of PV modules and W/Gs and (b) the number of generations evolved during the GA-based optimization process evolution.

6. Conclusions

In this paper, a methodology for the optimal sizing of desalination systems power-supplied by PV and W/G energy sources has been presented. The optimal number and type of each system component is calculated, such that the 20-year round total system cost is minimized, while simultaneously the consumer's water demand is completely covered. The 20-year round total system cost is equal to the sum of the respective components capital and maintenance costs. The total cost function minimization is implemented using genetic algorithms, which have the ability to calculate the global optimum in the overall state space with relative computational simplicity.

Table 10
The optimal sizing results for various types of power source supplying the residential household's and the community's desalination systems.

		N_{PV}	N_{WG}	N_{BAT}	N_{ch}^{PV}	N_{RO}	β (°)	W_{TANK} (l)	h (m)	Total cost (€)
Residential household	Only PV	36	–	4	13	1	70	6426	–	69,627.35
	Only W/G	–	17	2	–	1	–	9726	13	76,077.43
	Hybrid	7	7	2	2	1	39	6400	11	51,892.13
Community	Only PV	166	–	8	60	1	2	9230	–	214,889.2
	Only W/G	–	47	34	–	1	–	9855	15	289,042.0
	Hybrid	26	15	12	9	1	34	9828	13	133,473.6

The proposed method has been applied and tested for the design of two different desalination systems, which cover the potable water demands of a small community and of a residential household, respectively, in order to prove its effectiveness in various desalination system size scales. According to the optimal sizing results, the overall configuration cost is highly affected only by the capital cost which reaches the 72% and 84% of the total cost for the household and the community, respectively. The operational cost is mostly affected by the operational characteristics of the devices comprising the system, which influence the degree of exploitation of the available solar and wind energy potentials. In all cases examined, a significant part of the desalination system total capital cost is comprised by the cost of the batteries, which fluctuates between 15 and 35% depending on the PV modules inclination and the scale of the desalination system. Finally, using the hybrid PV–W/G configurations results in lower overall cost compared to desalination systems power-supplied by either PV, or W/G sources exclusively.

Nomenclature

N_P	number of PV modules connected in parallel
N_S	number of PV modules connected in series
$P_M^i(t,\beta)$	maximum output power of each PV power generation block on day i ($1 \le i \le 365$) and at hour t ($1 \le t \le 24$) (W)
$I_{SC}^i(t,\beta)$	PV module short-circuit current (A)
$I_{SC,STC}$	short-circuit current under STC (A)
$G^i(t,\beta)$	global irradiance incident on the PV module placed at tilt angle β (W/m^2)
K_I	short-circuit current temperature coefficient (A/°C)
$V_{OC}^i(t)$	open-circuit voltage (V)
$V_{OC,STC}$	open-circuit voltage under STC (V)
K_V	open-circuit voltage temperature coefficient (V/°C)
$T_A^i(t)$	ambient temperature (°C)
NOCT	nominal operating cell temperature (°C)
$FF^i(t)$	fill Factor
V_{DC}^m	battery charger maximum input voltage (V)
V_{OC}^m	PV modules maximum open-circuit voltage level (V)
β	PV modules tilt angle
β_1	PV modules tilt angle corresponding to the months from January until April and September until December
β_2	PV modules tilt angle corresponding to the months from May to August
$P_{PV}^i(t,\beta)$	PV power actually transferred to the battery bank by each PV power generation block (W)
n_s	battery charger power conversion factor
n_1	battery charger power electronic interface efficiency
n_2	conversion factor
N_{ch}^{PV}	total number of PV battery chargers
N_{PV}	total number of PV modules
P_{ch}^m	power rating of the selected battery charger (W)
P_{PV}^m	maximum power of one PV module under STC (W)
$P_{WG}^i(t,h)$	power transferred to the battery bank at hour t of day i from each W/G power generation block (W)
h	W/G installation height (m)
$v^i(t,h)$	wind speed (m/s) at height h
$v_{ref}^i(t)$	reference (input) wind speed (m/s) measured at height h_{ref}
h_{ref}	reference height (m)
α	wind speed law exponent
n_B^S	number of batteries connected in series
V_B	nominal voltage of each individual battery (V)
V_{BUS}	nominal DC bus voltage (V)
C_n	battery bank nominal capacity (Ah)
N_{BAT}	total number of batteries
C_B	nominal capacity of each battery (Ah)
DOD	maximum permissible battery depth of discharge (%)
C_{min}	minimum permissible battery bank capacity during discharging (Ah)
$C^i(t)$	available battery capacity (Ah) at hour t
n_B	battery round-trip efficiency
$P_B^i(t)$	battery input/output power (W)
Δt	simulation time step
N_{WG}	total number of W/G power generation blocks
$P_L^i(t)$	total DC power input to the DC/AC inverters at hour t of day i (W)
$P_{RO}^i(t)$	total AC power supplying the desalination units (W)
n_i	power conversion efficiency of the DC/AC inverters
$P_u^i(t)$	AC power consumption of each RO unit (W)
N_{RO}	number of desalination units
$W_{RO}^i(t)$	total volume of desalinated water produced by the desalination units at hour t of day i (m^3)
$W_u^i(t)$	water production of each RO unit (m^3)
W_{min}	minimum permissible amount of water stored in the tank (m^3)
W_{TANK}	tank total volume (m^3)
$W^i(t)$	volume of the available water stored in the tank at hour t of day i (m^3)
P_{FL}(W)	total consumed amount of the AC power (W)
W_{FL}	water stored in the tank (m^3)
$P_{u,FL}$	power consumption of each RO unit during the flushing process (W)
$W_{u,FL}$	water consumption of each RO unit during the flushing process (m^3)
$W_D^i(t)$	desalination system consumer's water demand at hour t of day i
C_{PV}	capital cost of the PV modules
C_{WG}	capital cost of the W/Gs
C_{BAT}	capital cost of the batteries
C_{INV}	capital cost of the DC/AC inverters
C_{ch}^{PV}	capital cost of the PV battery chargers
C_{TANK}	capital cost of the water storage tank per m^3
C_{RO}	capital cost of the RO desalination units
C_h	capital cost of the W/G installation tower (per m)
M_{PV}	annual maintenance costs of the PV modules
M_{WG}	annual maintenance costs of the W/Gs
M_{BAT}	annual maintenance costs of the batteries
M_{INV}	annual maintenance costs of the DC/AC inverters
M_{ch}^{PV}	annual maintenance costs of the PV battery chargers
M_{TANK}	annual maintenance costs of the water storage tank per m^3
M_{RO}	annual maintenance costs of the RO desalination units
M_h	annual maintenance costs of the W/G installation tower (per m)
Y_{BAT}	expected number of battery replacements during the 20-year system operation
Y_{ch}^{PV}	expected number of the PV battery chargers replacements during the 20-year system operation
Y_{INV}	expected number of the DC/AC inverters replacements during the 20-year system operation
p_{sc}	simple crossover probability
p_{sac}	simple arithmetic crossover probability
p_{wac}	whole arithmetic crossover probability
p_{um}	uniform mutation probability
p_{bm}	boundary mutation probability
p_{nm}	non-uniform mutation probability
N	number of chromosomes

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